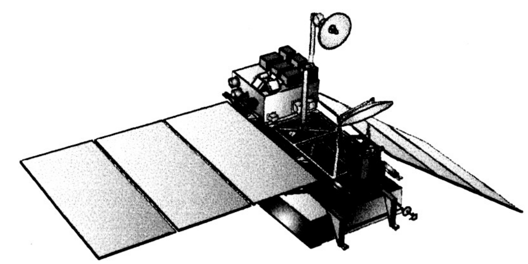
GPM

Global Precipitation Measurement (GPM) Mission

An International Partnership &
Precipitation Satellite Constellation

for Research
on Global Water & Energy Cycle



NASA's Scientific Agenda for GPM Mission

- **3rd GPM International Planning Meeting**
- NASA/Goddard Space Flight Center, Greenbelt, MD 20771
- [tel: 301-286-5770; fax: 301-286-1626; eric.a.smith@nasa.gov; http://gpmscience.gsfc.nasa.gov]
- June 24-26, 2003; ESA/ESTEC, Noordwijk, The Netherlands

GPM Mission Design

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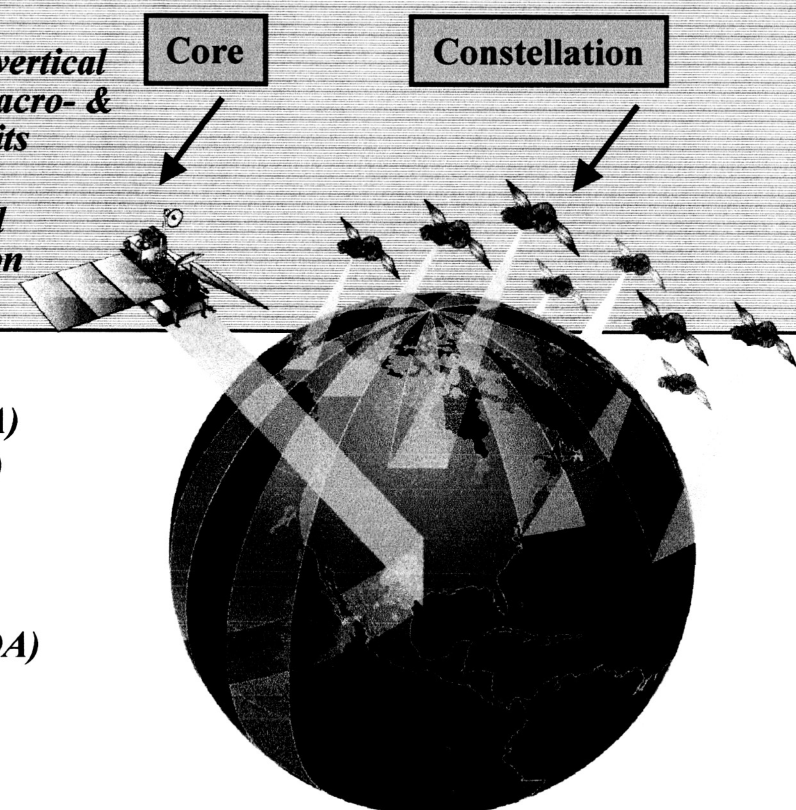
OBJECTIVES
- Understand horizontal & vertical structure of rainfall, its macro- & micro-physical nature, & its associated latent heating
- Train & calibrate retrieval algorithms for constellation radiometers



OBJECTIVES
- Provide sufficient global sampling to significantly reduce uncertainties in short-term rainfall accumulations
- Extend scientific and societal applications

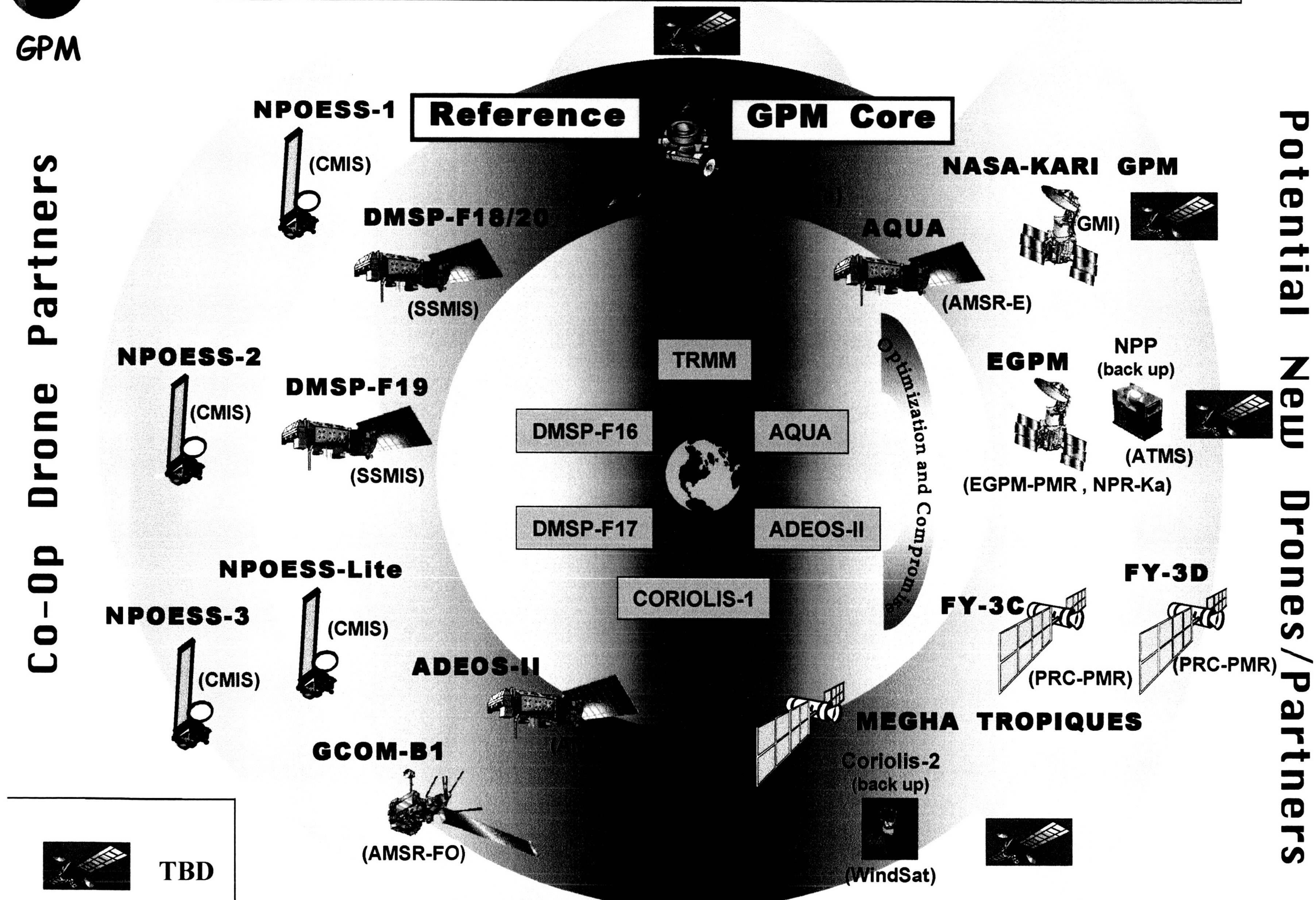
Core Satellite
- TRMM-like spacecraft (NASA)
- H2-A rocket launch (NASDA)
- Non-sun-synchronous orbit
  ~ 65° inclination
  ~400 km altitude
- Dual frequency radar (NASDA)
  K-Ka Bands (13.6-35 GHz)
  ~ 4 km horizontal resolution
  ~250 m vertical resolution
- Multifrequency radiometer (NASA)
  10.7, 19, 22, 37, 85, (150/183 ?) GHz V&H

Precipitation Processing Center
- Produces global precipitation products
- Products defined by GPM partners

Constellation Satellites
- Pre-existing operational-experimental & dedicated satellites with PMW radiometers
- Revisit time
  3-hour goal at ~90% of time
- Sun-synch & non-sun- synch orbits
  600-900 km altitudes

Precipitation Validation Sites for Error Characterization
- Select/globally distributed ground validation "Supersites" (research quality radar, up looking radiometer-radar-profiler system, raingage-disdrometer network, & T-q soundings)
- Dense & frequently reporting regional raingage networks

Notional International Constellation Architecture



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GPM Mission is Being Formulated within Context of Global Water & Energy Cycle with Foremost Science Goals Focusing On

- **Improved Climate Predictions:** through *quantifying trends & space-time variations in rainfall* with associated *error bars* and improvements in achieving *water budget closure from low to high latitudes* -- plus focused GCM research on understanding *relationship between rain microphysics/latent heating/DSD properties & climate variations* as mediated by accompanying *accelerations in global water cycle* (both atmosphere & surface branches).

- **Improved Weather Predictions:** through *accurate, precise, frequent & globally distributed measurements* of instantaneous *rainrate & latent heat release* -- plus focused NWP research on advanced techniques in *satellite precipitation data assimilation & error characterization* of precipitation retrievals.

- **Improved Hydrometeorological Predictions:** through *frequent sampling & complete continental coverage* of *high resolution rainfall* measurements including *snowfall* -- plus focused research on *innovative designs in hydrometeorological modeling* encompassing *hazardous flood* forecasting, *seasonal draught-flood* outlooks, & *fresh water resources* prediction.

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Relevance of Global Water Cycle

Availability & quality of water is essential to life on earth.

- **GWC is core of climate-weather-hydrology system, affecting all physical, chemical, & ecological components & their interactions.**
- **Accurate assessment of spatial-temporal variation of land surface water cycle is essential for addressing wide variety of socially relevant science, education, applications, & management issues:**
  - rainfall-runoff, flood, & drought prediction
  - meteorological processes & weather prediction
  - climate system & ecosystem modeling
  - soil system science
  - crop systems & agriculture production
  - water supply, human health, & disease
  - forest ecology & management
  - civil engineering
  - water resources management
  - military operations

- **Additionally, as people increasingly m[...] stal ocean, concern grows about ensuing [...] her, climate, water supplies, crop production, biogeochemical cycles, & ecological balances of biosphere at various time scales.**

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I

Sampling Frequency & Global Coverage

Percent Sampling of 3-Hr Bins & Global Mean Revisit Time

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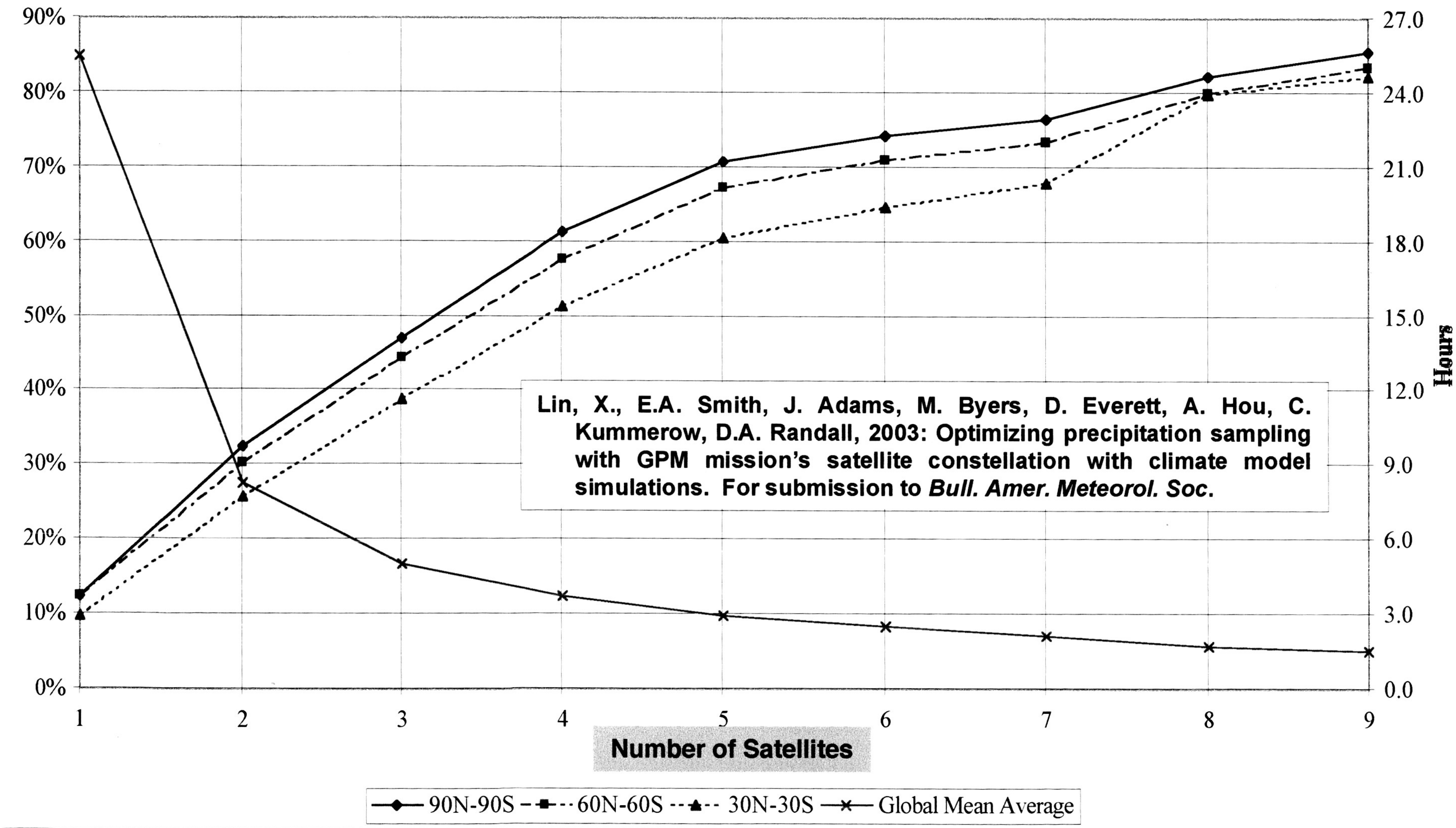
CORE DMSP/F18 DMSP/F19 NPOESS/Lite GCOM-B1 NGPM EGPM MEGHA-TROPIQUES FY-3



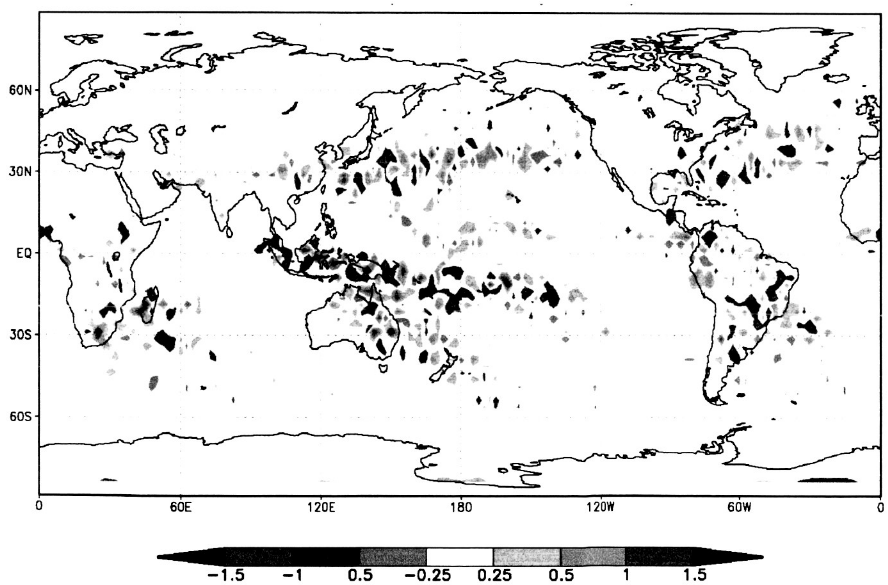
Observing Simulation System Experiment (OSSE) for Orthodox 8-Member Sun-Synchronous Constellation Producing Global 3-Hour Sampling

[Flown at Two Swath Widths]

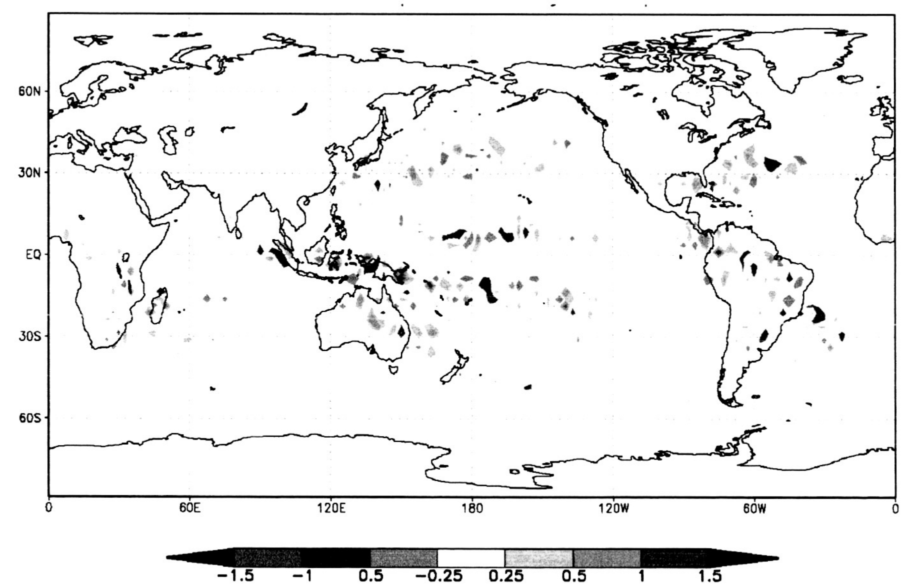
Precipitation field produced by Colorado State University General Circulation Model (GCM) simulating January conditions

[characteristic monthly errors order 0.25 mm day^{-1} or ~7 W m^{-2}]

800 km Swath Width viz TMI

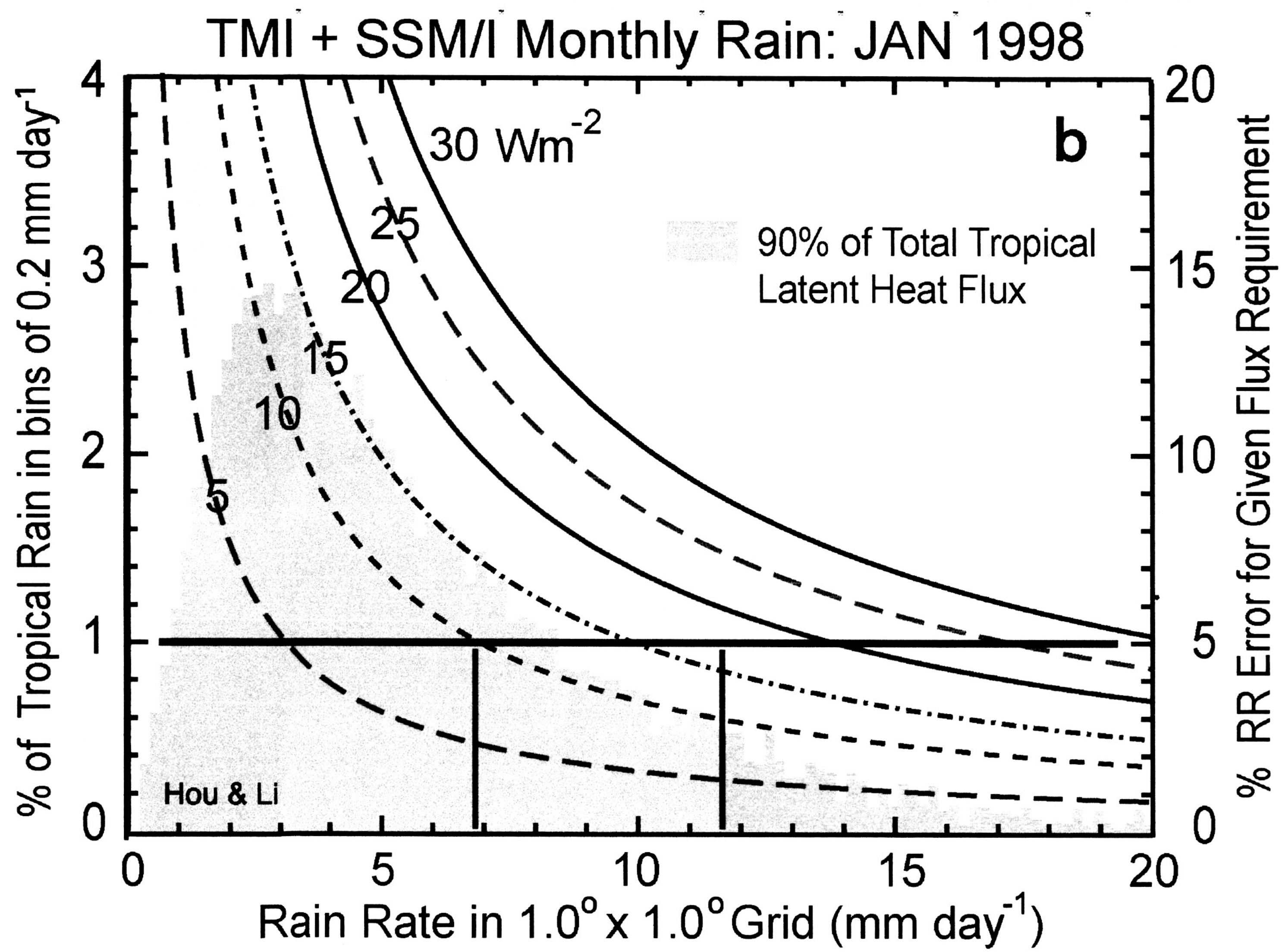


1600 km Swath Width viz SSM/I

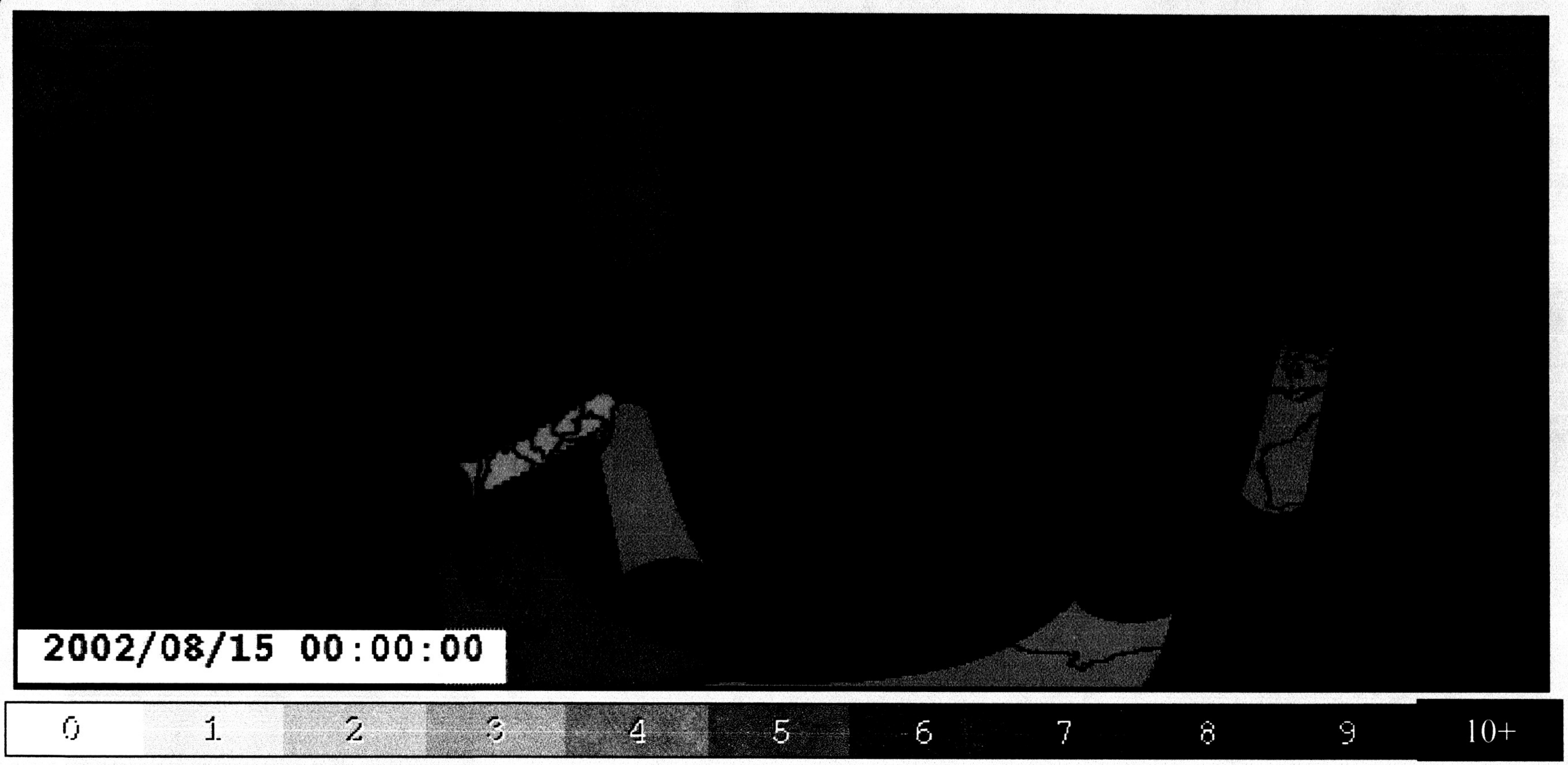


Rainfall Deviations (satellite sampled minus fully sampled in mm day^{-1})

Quantification & Interpretation of Required Precipitation Accuracy in Context of Tolerable Energy Flux Error



TRMM-EOS Era: Worst Case Revisit Time Is ~ 6 hours



Revisit (Hours Since Previous Overpass)

Gold:	SSMI from DMSP F-13, F-14, F-15 (conical)
Green:	AMSU-B from NOAA-15, NOAA-16, NOAA-17 (x-track)
Blue:	TMI from TRMM (conical)
Red:	AMSR-E from EOS-Aqua (conical)(shaded regions represent 15-minute coverage)

Turk, F.J., E. Ebert, B-J. Sohn, H-J. Oh, V. Levizzani, E.A. Smith, & R. Ferraro, 2002: Validation of global operational blended-satellite precipitation analysis at short time scales. *Bull. Amer. Meteorol. Soc.*, for submission.

II
Measurement Resolution & Microphysical Dexterity

Improving Precipitation Retrievals

Cloud Macrophysical & Microphysical Fundamentals

Determination of:
drop size distribution [DSD(r)],
mass mixing ratio [$q(z)_{hydro(r)}$],
rain mass flux [$F_r(z)$],
fall velocity [$w(z)_{hydro(r)}$],
& latent heating [LH(z)]

$$q(z)_{hydro(r)} = \sigma_w \,(4/3\pi r^3)\, DSD(r)$$

$$w(z)_{hydro(r)} = GFO\,[q(z)_{hydro(r)}]$$

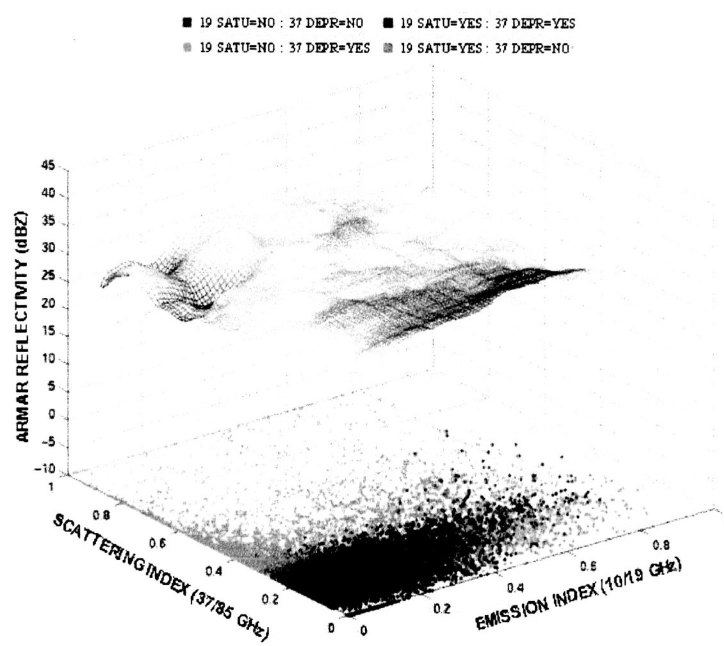
$$F_r(z) = \int q(z)_{hydro(r)}\, w(z)_{hydro(r)}\, dr$$

$$LH(z) = C\,[\partial F_r(z)/\partial z]$$

$$RR(z) = F_r(z) / \sigma_w$$

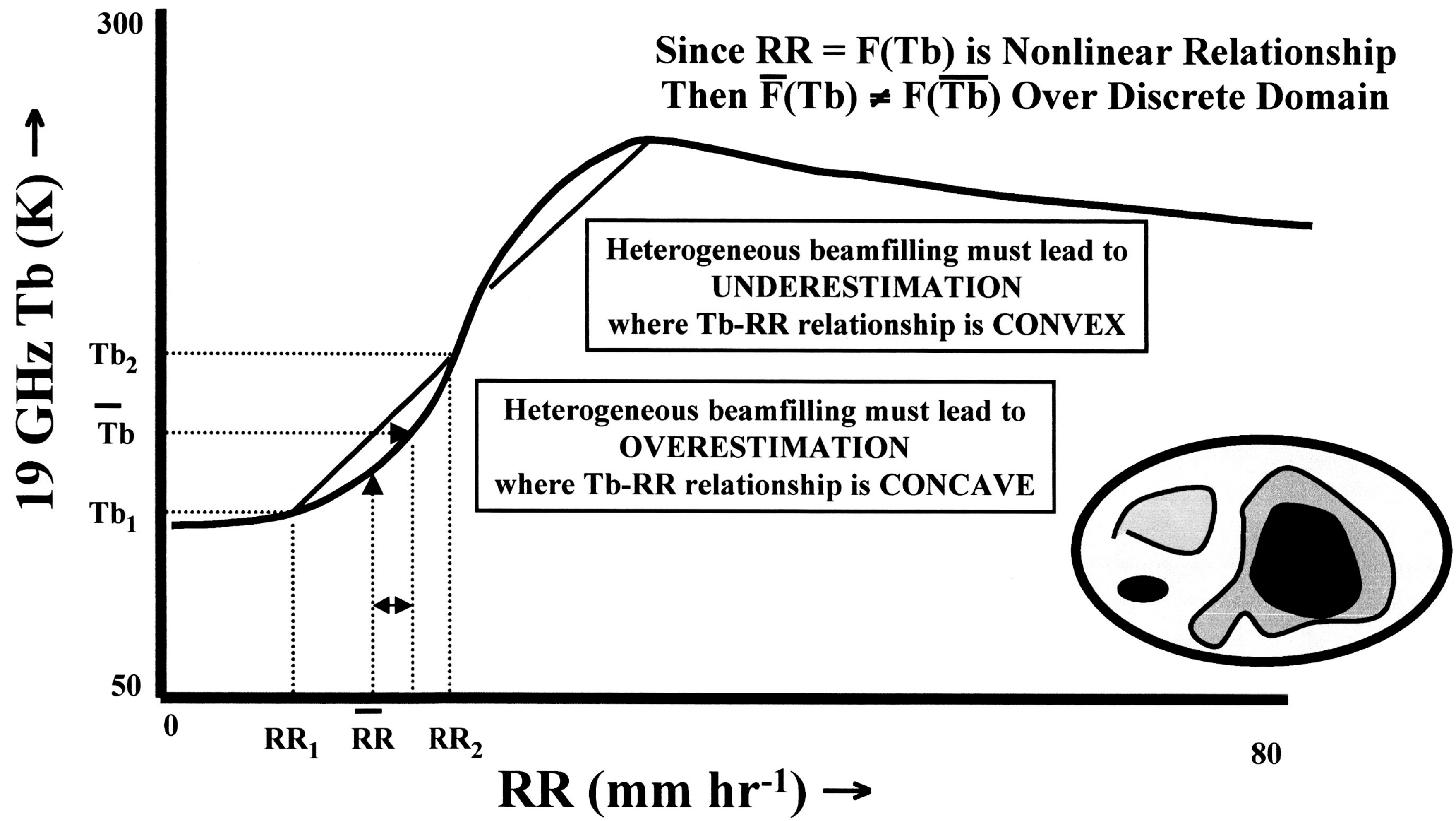
$$RF_{sur} = RR(z_{sur}) \bullet \Delta t$$

3-D KWAJEX AMPR V4.0 E-S INDEX WITH 0.5-1 KM LAYER ARMAR REFLECTIVITY
28 FLIGHTS TOTAL --- 40140 SUPERPIXELS



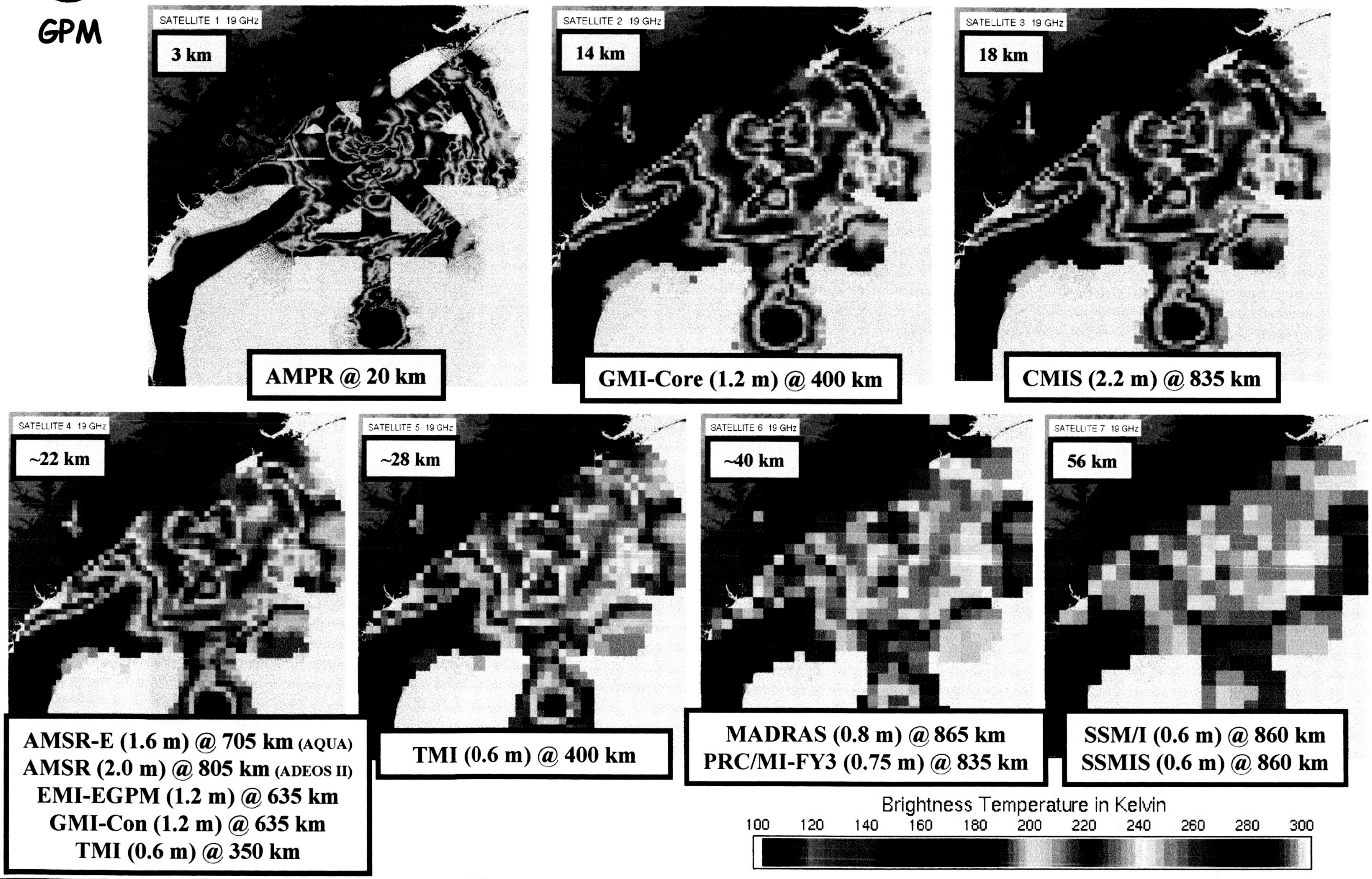
Implementation of Fully Modular OPEN ACCESS Facility Algorithms Accompanied by COMPREHENSIVE TESTING Capability within PPS

Resolution Above All Else because Beamfilling Error Rules!

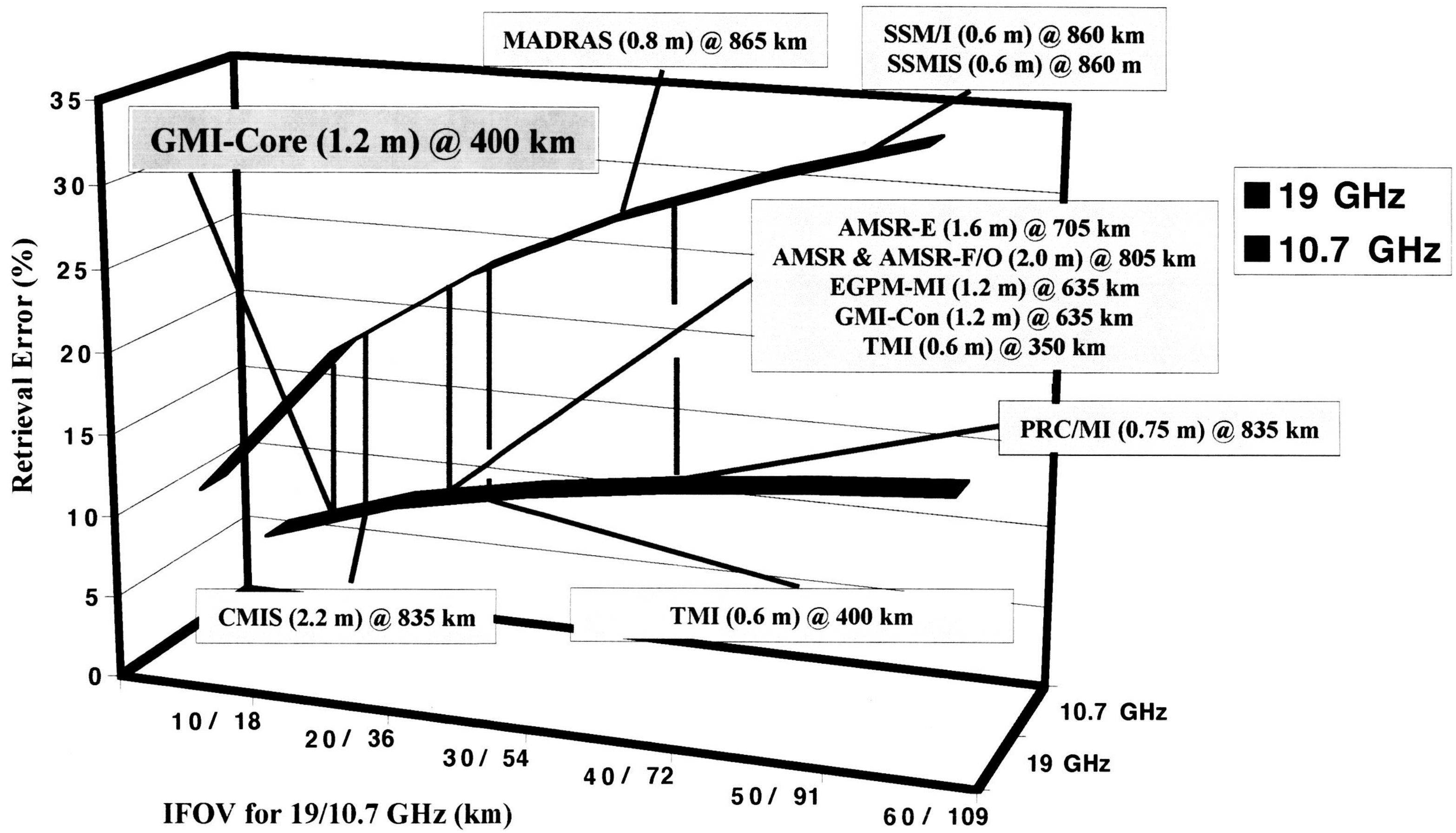


Smith, E.A., and S.Q. Kidder, 1978: A multispectral satellite approach to rainfall estimates. In *The Use of Satellite Data in Rainfall Monitoring* (authored by E.C. Barrett and D.W. Martin), Academic Press, 160-163.

Hurricane Bonnie at 19 GHz



Beam Filling Induced Retrieval Error at 10.7 & 19 GHz as Function of IFOV



	10/ 18	20/ 36	30/ 54	40/ 72	50/ 91	60/ 109
■19 GHz	11.4	20.6	25.9	29.7	32.6	35
■10.7 GHz	5.9	8.7	10.3	11.5	12.4	13.1

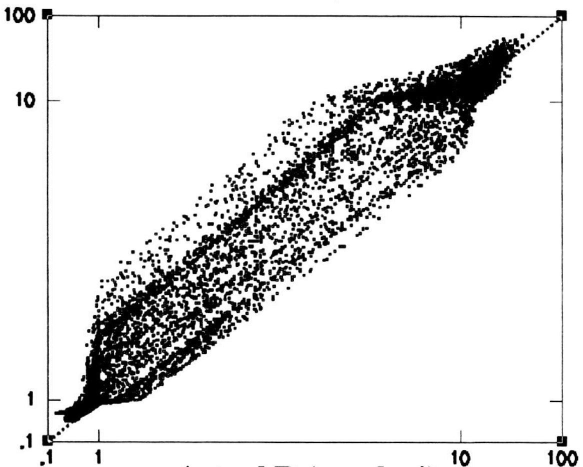
Wang, S.A., 1996: Modeling the beamfilling correction for microwave retrieval of oceanic rainfall. Ph.D. Dissertation, Dept. of Meteorology, Texas A&M University, College Station, TX, 100 pp. [T.T. Wilheit, Major Professor]

TRMM & GPM Rainrate Retrieval Simulations Under Varying Mean Adj Drop Diameter Profiles

[simulations based on Monte Carlo proliferation of Hurricane Bonnie observations]

TRMM Single-Frequency Algorithm

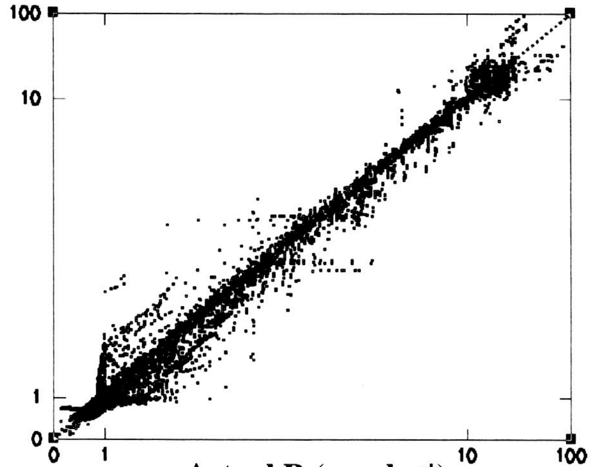
(bias due to irretrievable DSD variability)



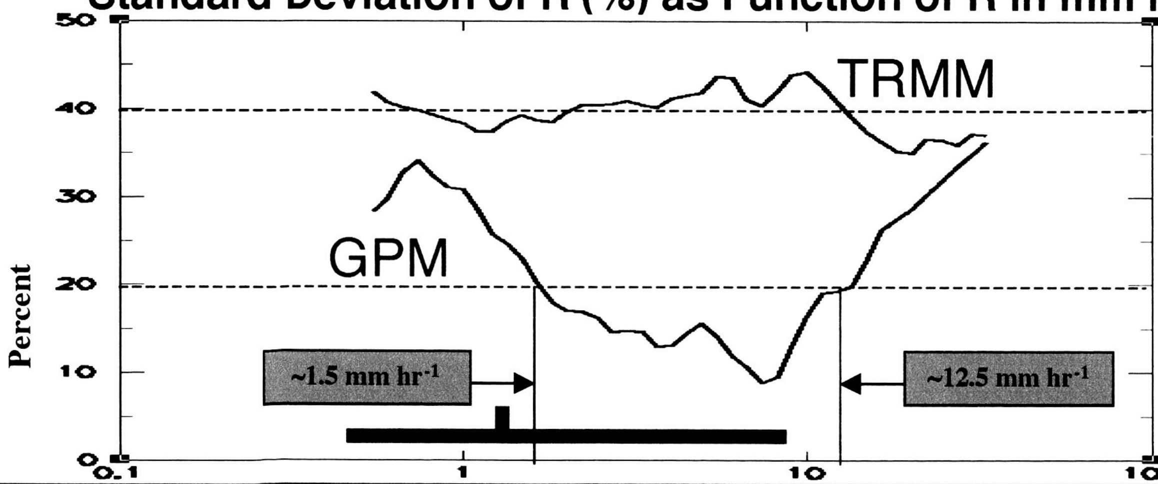
Retrieved R (mm hr^{-1})

GPM Dual-Frequency Algorithm

(near-zero bias & reduced scatter in mid-range)



Standard Deviation of R (%) as Function of R in mm hr^{-1}



95% of LH spectra

modal value of LH

with R approximately log-normal then σ_R proportional to R

exact variability depends on DSD variability in altitude

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III
Global Water Cycling & Climate

Global Water Budget & Water Cycle

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General Equation

water tendency + water divergence = phase changes + turbulent eddy diffusion

$$\partial \overline{q(p)} / \partial t + \nabla \bullet \overline{\vec{U}(p)\, q(p)} + \partial \overline{\omega(p)\, q(p)} / \partial p = S(q) + D(q)$$

Employing Reynolds Decomposition and Ignoring Horizontal Eddy Fluxes

total water tendency (vapor or cloud water) | vapor or cloud water divergence | evaporation sublimation | condensation deposition | Div vertical eddy transport of vapor or cloud water

$$\partial \overline{q_v(p)} / \partial t + \nabla \bullet \overline{\vec{U}(p)\, q_v(p)} + \partial \overline{\omega(p)\, q_v(p)} / \partial p = + \overline{e(p)} - \overline{c(p)} - \partial \overline{[\omega(p)'\, q_v(p)']} / \partial p$$

$$\partial \overline{q_c(p)} / \partial t + \nabla \bullet \overline{\vec{U}(p)\, q_c(p)} + \partial \overline{\omega(p)\, q_c(p)} / \partial p = - \overline{e(p)} + \overline{c(p)} - \partial \overline{[\omega_c(p)'\, q_c(p)']} / \partial p$$

Vertically Integrate

combined vapor & cloud water storage | vapor advection | cloud water advection | surface evaporation | surface precipitation

$$\partial \overline{W_t} / \partial t + \overline{\nabla \bullet \vec{U} W_v} + \overline{\nabla \bullet \vec{U} W_c} = \overline{E} - \overline{P} \qquad \textbf{Divergence Form}$$

$$\partial \overline{W_t} / \partial t + \overline{\vec{U} \bullet \nabla W_v} + \overline{\vec{U} \bullet \nabla W_c} = \overline{E} - \overline{P} \qquad \textbf{Advection Form}$$

where $\overline{W_v \bullet \nabla \vec{U}} = 0$ and $\overline{W_c \bullet \nabla \vec{U}} = 0$ signifying no mass divergence out of column

Acceleration of Water Cycle

What is Acceleration of Water Cycle in Oceanic Context?

first, above derivation gives water budget in divergence form, as follows

storage		vapor & cloud water advection				evaporation		precipitation
$\partial \overline{W_t} / \partial t$	+	$\overline{\nabla \cdot \vec{U} W_v}$	+	$\overline{\nabla \cdot \vec{U} W_c}$	=	$\overline{E}$	-	$\overline{P}$

thus, acceleration of oceanic water budget is rate of change of

combined vapor & cloud water storage		vapor advection		cloud water advection		surface evaporation		surface precipitation
$\partial^2 \overline{W_t} / \partial t^2$	+	$\partial \overline{\nabla \cdot \vec{U} W_v} / \partial t$	+	$\partial \overline{\nabla \cdot \vec{U} W_c} / \partial t$	=	$\partial \overline{E} / \partial t$	-	$\partial \overline{P} / \partial t$

What is Acceleration of Water Cycle in Continental Context?

first, continental water budget is formulated differently than oceanic budget

storage		interflow		runoff & base flow		precipitation		evaporation
$\dot{\overline{S}}$	+	$\overline{\vec{U}_s \cdot \nabla q_l}$	+	$\overline{RO} + \overline{BF}$	=	$\overline{P}$	-	$\overline{E}$

thus, acceleration of continental water budget is rate of change of

storage of soil moisture & surface water & surface snow-ice		interflow (soil water advection)		surface runoff & base flow-recharge		surface precipitation & deposition & tree leaf-needle drip & canopy snow blowoff		surface evaporation & ground-leaf-snow transpiration-ET & sublimation
$\partial \dot{\overline{S}} / \partial t$	+	$\partial \overline{\vec{U}_s \cdot \nabla q_l} / \partial t$	+	$\partial (\overline{RO} + \overline{BF}) / \partial t$	=	$\partial \overline{P} / \partial t$	-	$\partial \overline{E} / \partial t$

Satellite-based Water Budget of Gulf of Mexico & Caribbean Basins

[P. Santos & E.A. Smith, 2003]

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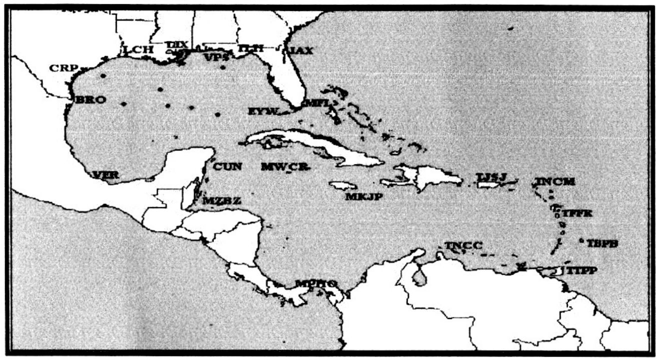
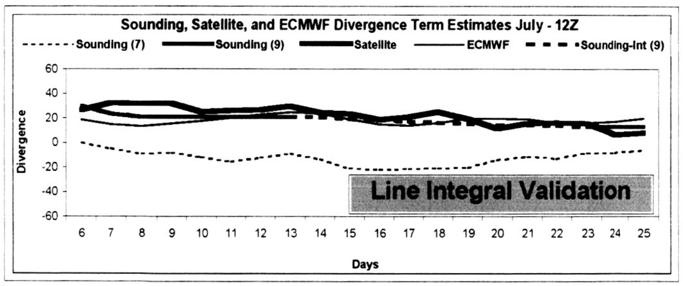
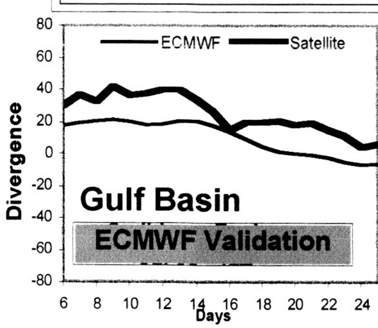
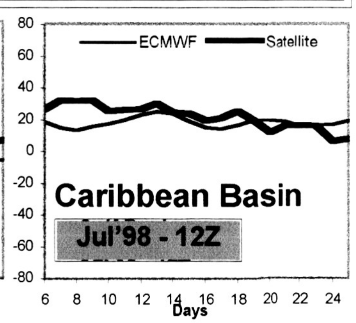
Gulf-Caribbean Basins & Upper Air/Buoy Validation Data Sites





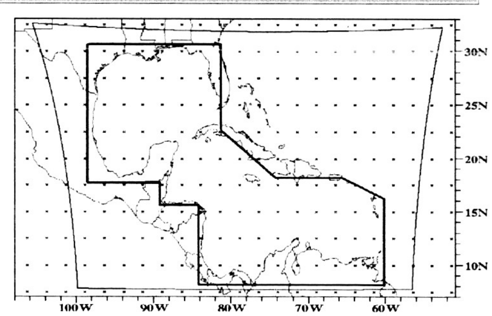




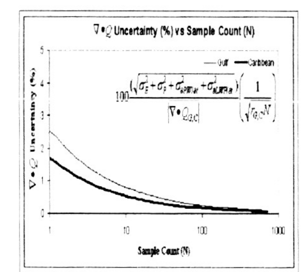
Design of Algorithm System

- **Precipitable Water**: SSM/I; GOES; Combined SSM/I-GOES
- **Cloud LWP**: SSM/I; Combined SSM/I-GOES
- **Evaporation**: SST GOES; Ws SSM/I; qs GOES; qa SSM/I GOES; Ta GOES
- **Precipitation**: SSM/I; Combined TRMM-SSM/I & GOES

Study Area, GOES-SSM/I-TRMM Sectors, & ECMWF Grid



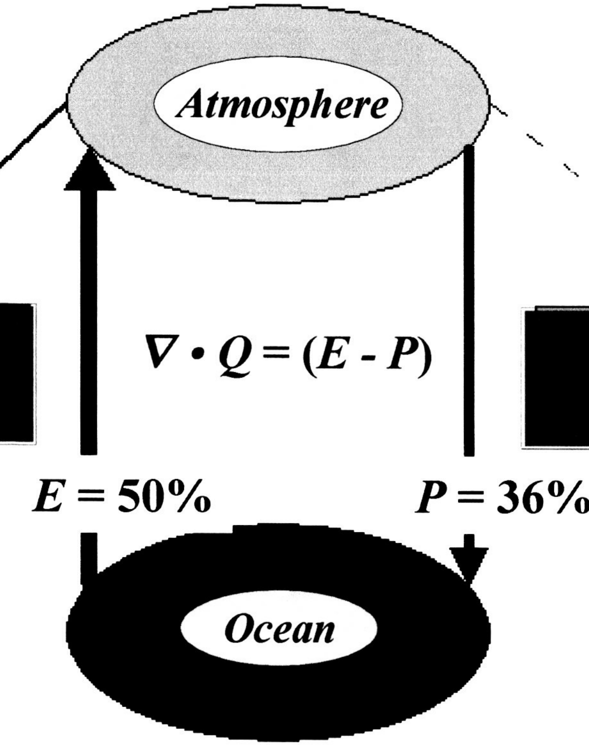
∇•Q Uncertainty (%) vs Sample Count (N)

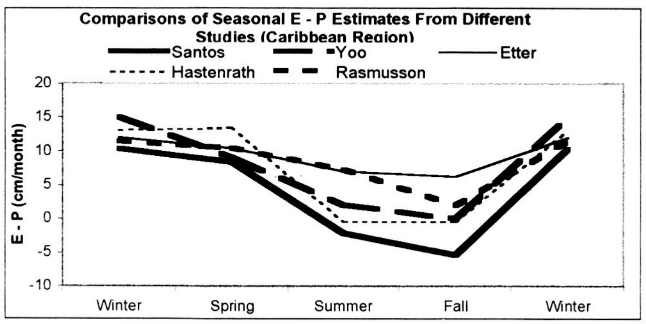


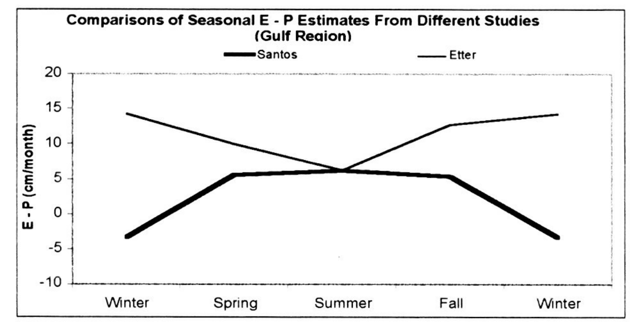
$$\left[\frac{\partial(PW+LWP)}{\partial t}\right]+\left[\nabla\bullet Q\right]=\left[E-P\right]$$

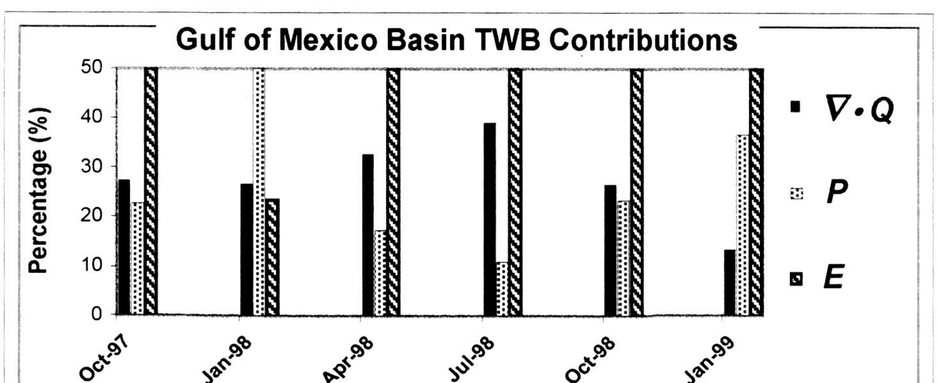
$$(\nabla\bullet Q)_{i,j,t} = (E - P)_{i,j,t} - \{[(PW + LWP)_{i,j,t+\Delta t} - (PW + LWP)_{i,j,t-\Delta t}] / 2Dt\}$$

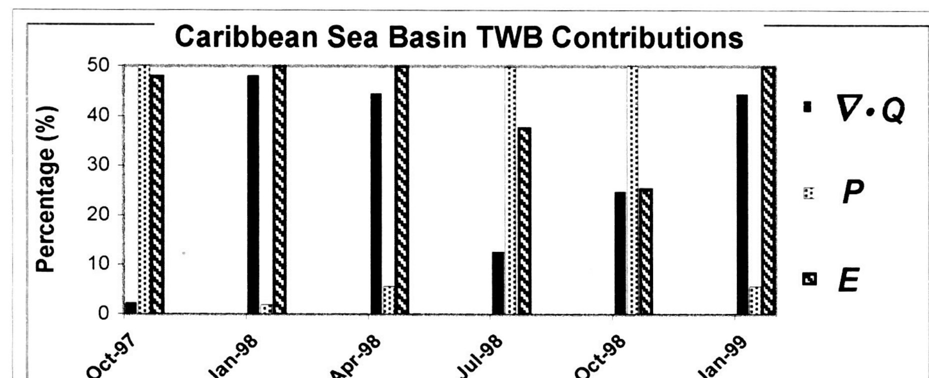
Fully-Averaged Monthly Framework





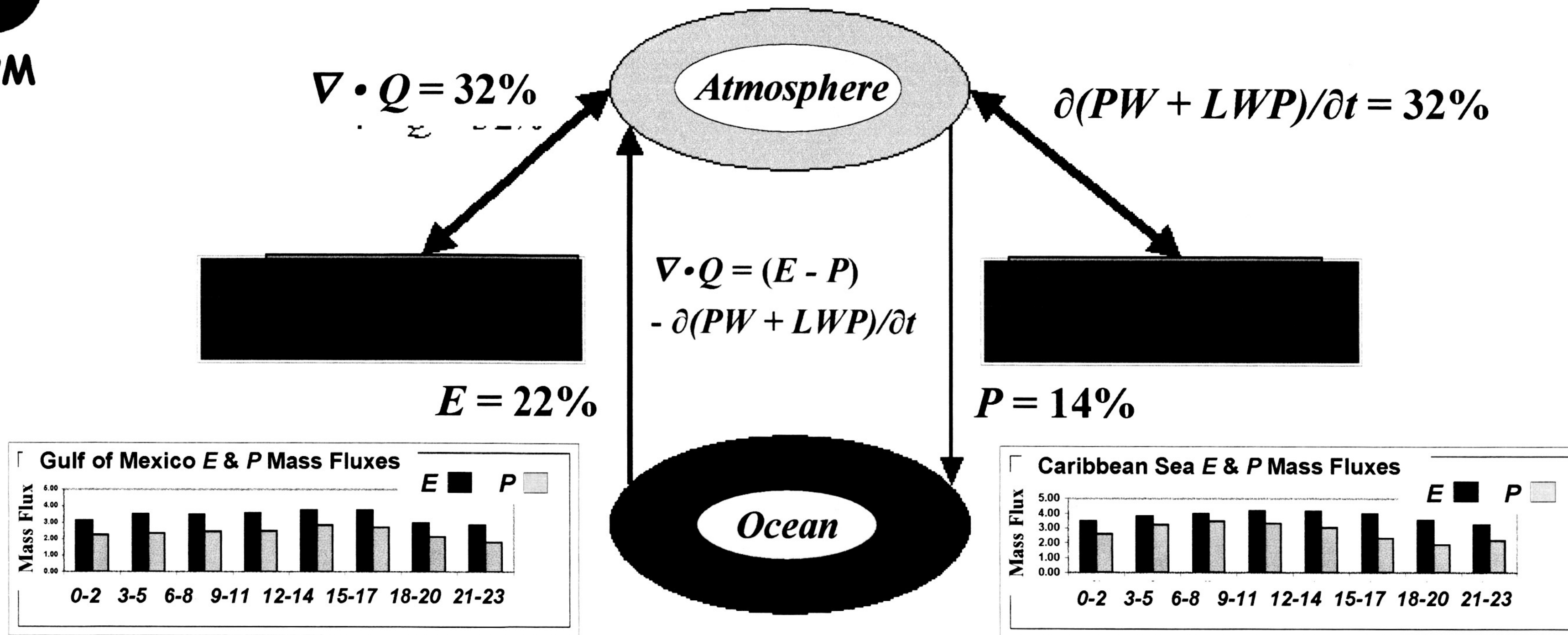


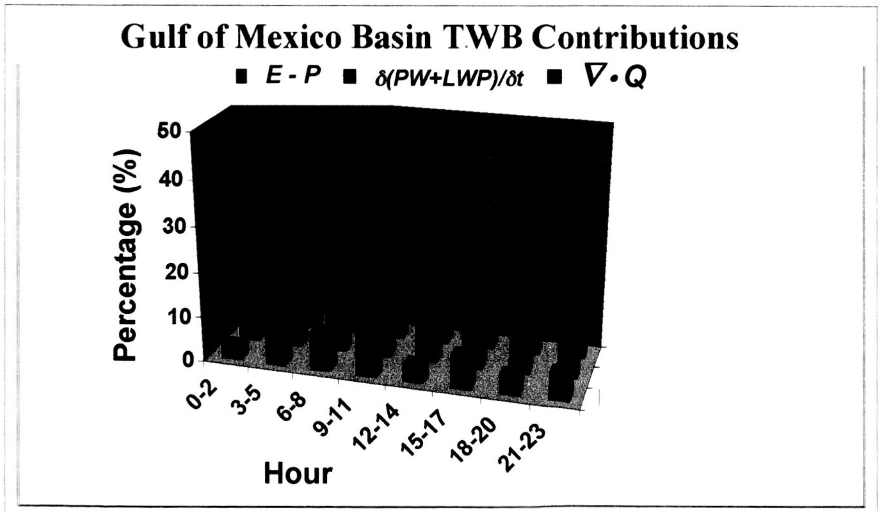


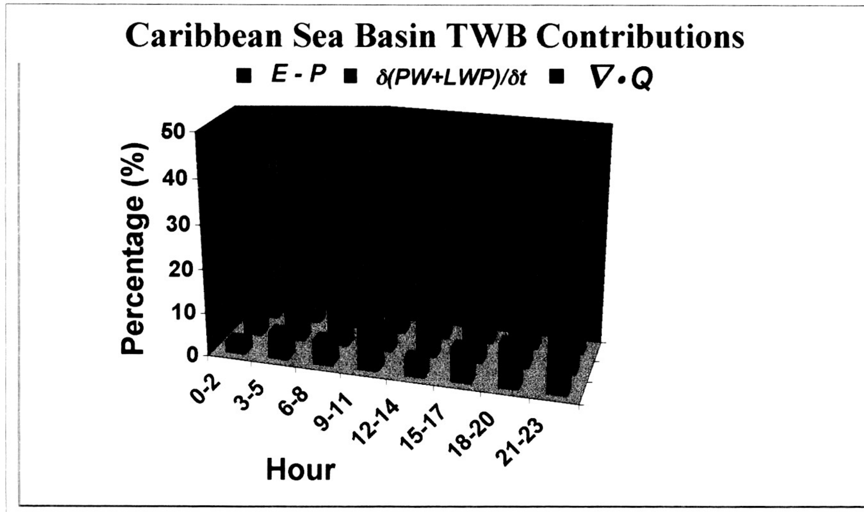


$C_{TWB} = \langle T \rangle \,/\, [\langle \partial PW / \partial t \rangle + \langle \partial LWP / \partial t \rangle + \langle P \rangle + \langle E \rangle]$ $\langle\ \rangle \equiv$ *absolute value*

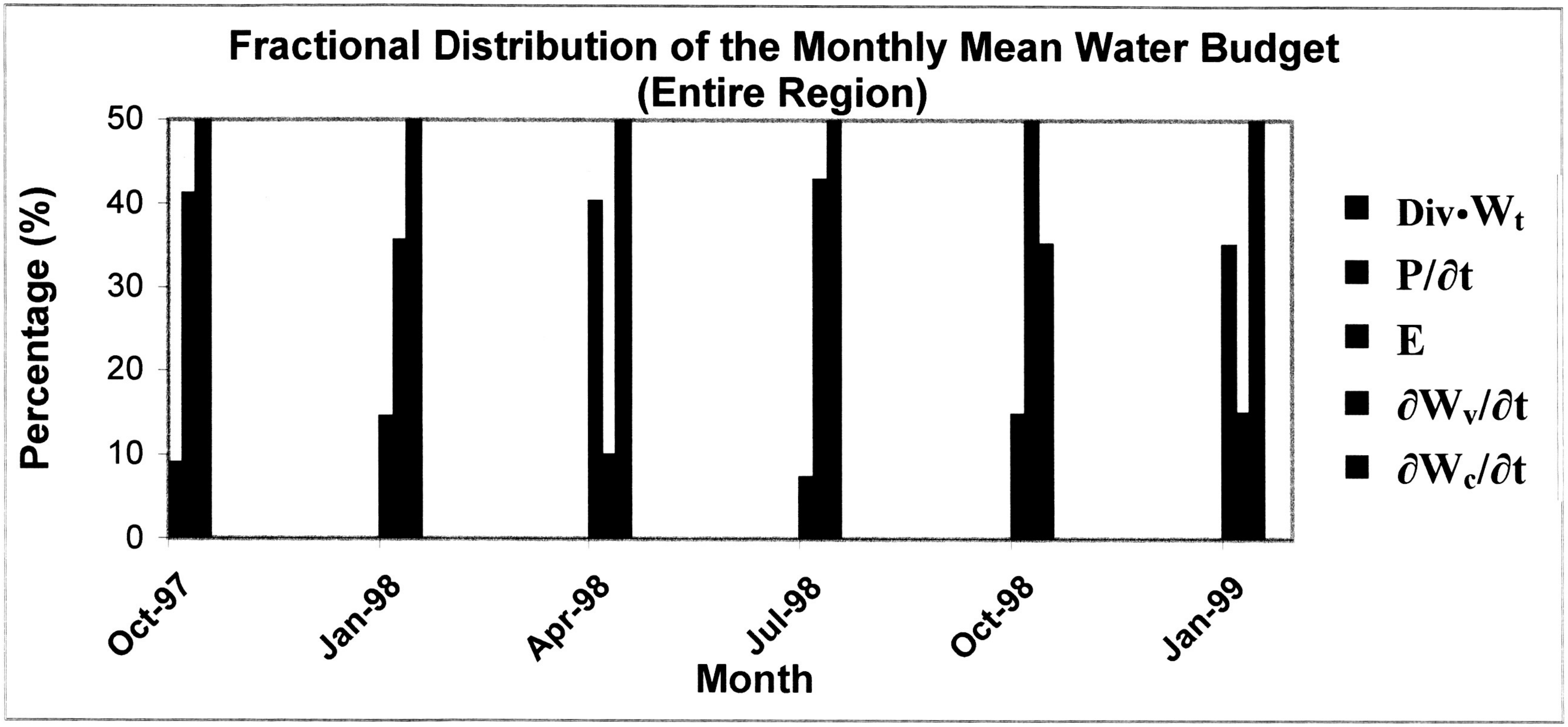
Diurnally-Averaged Monthly Framework

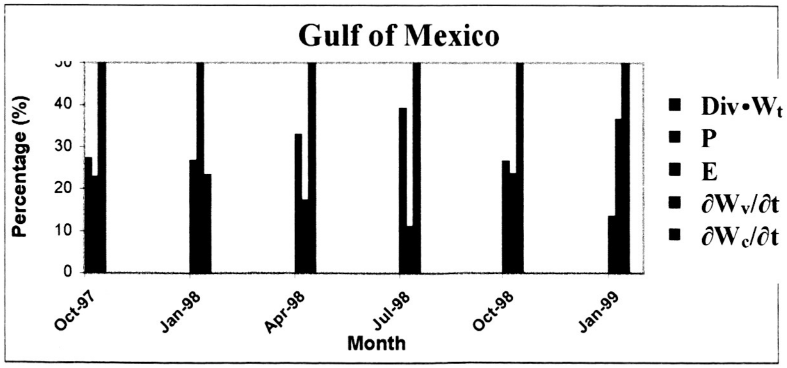


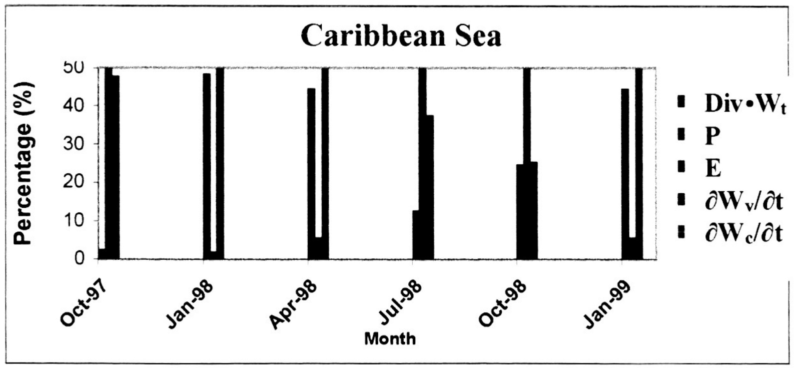




Summary of Water Budget Calculations







Precipitation Prediction: Key Objective of Water Cycle Research

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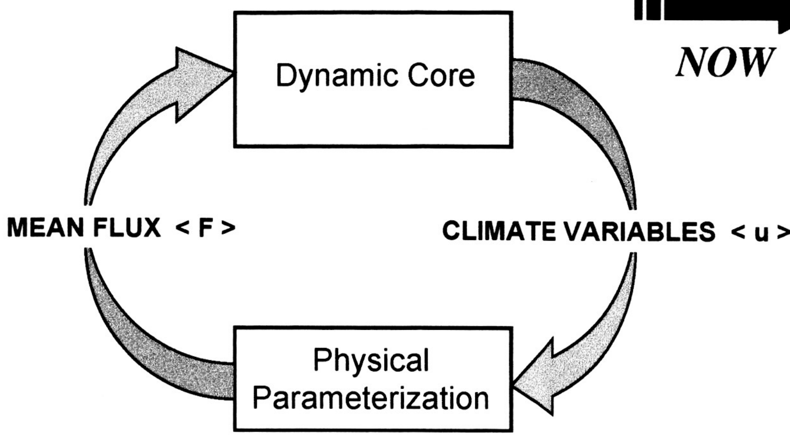
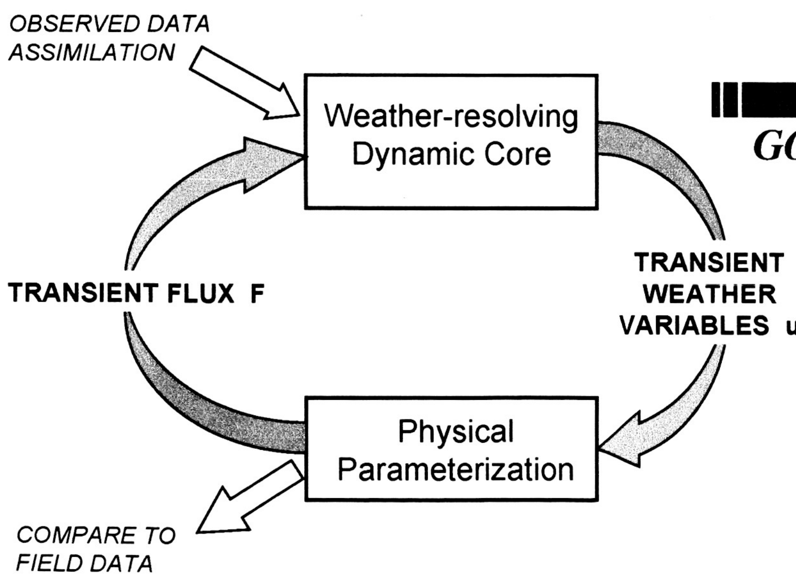


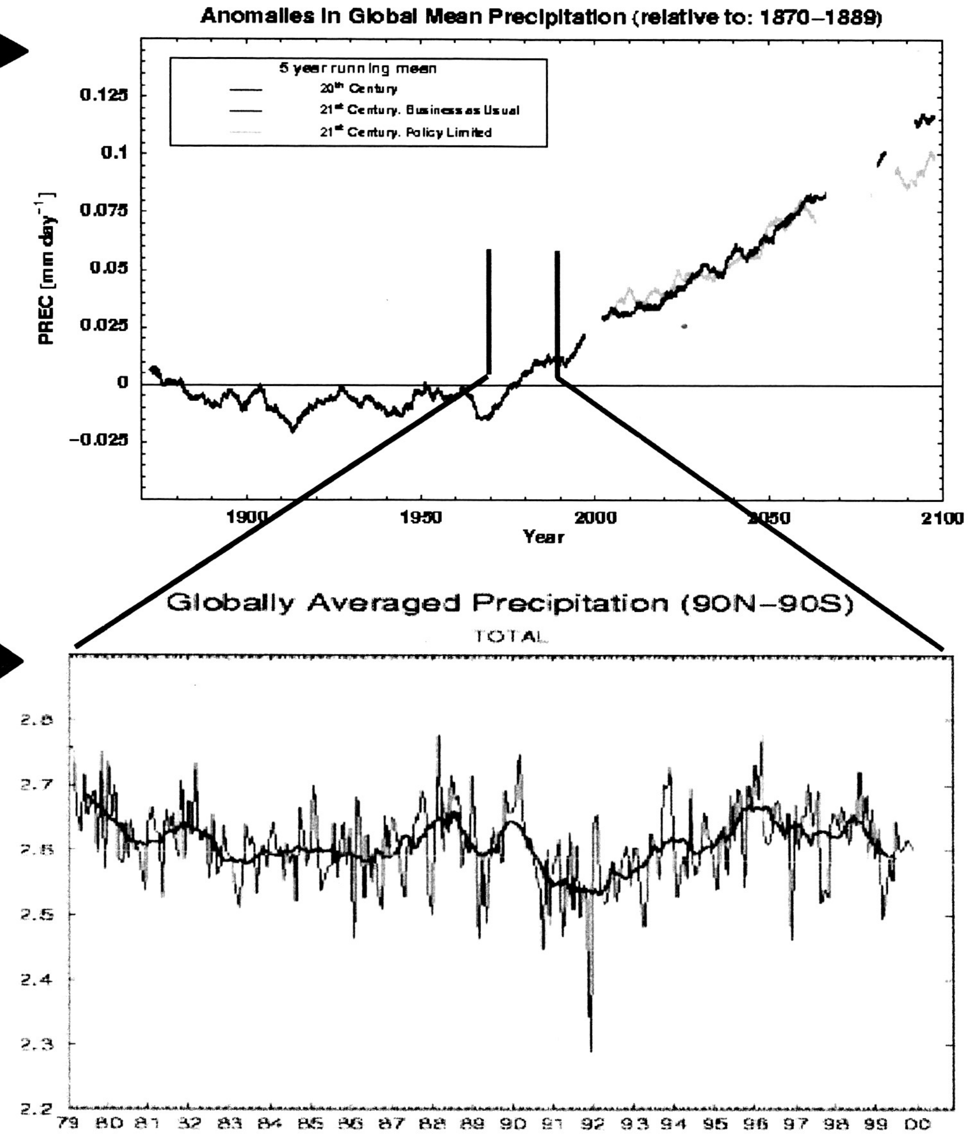
NOW

State of Art Climate Model (CCSM)



GOAL

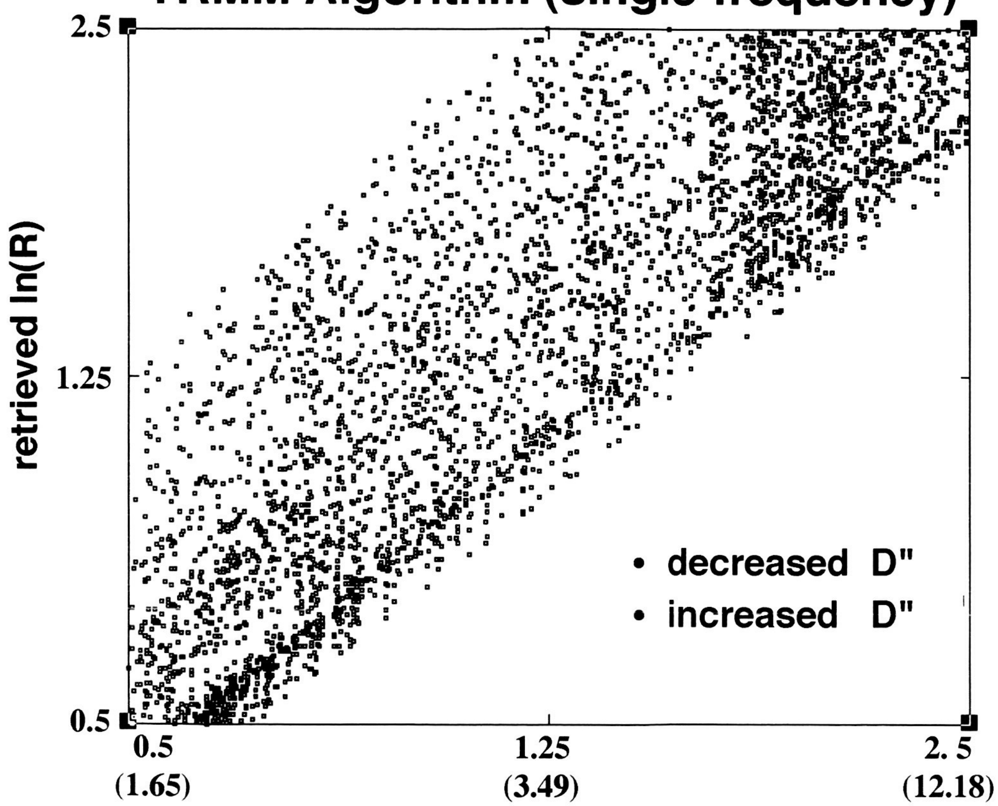
Next Generation Climate Model



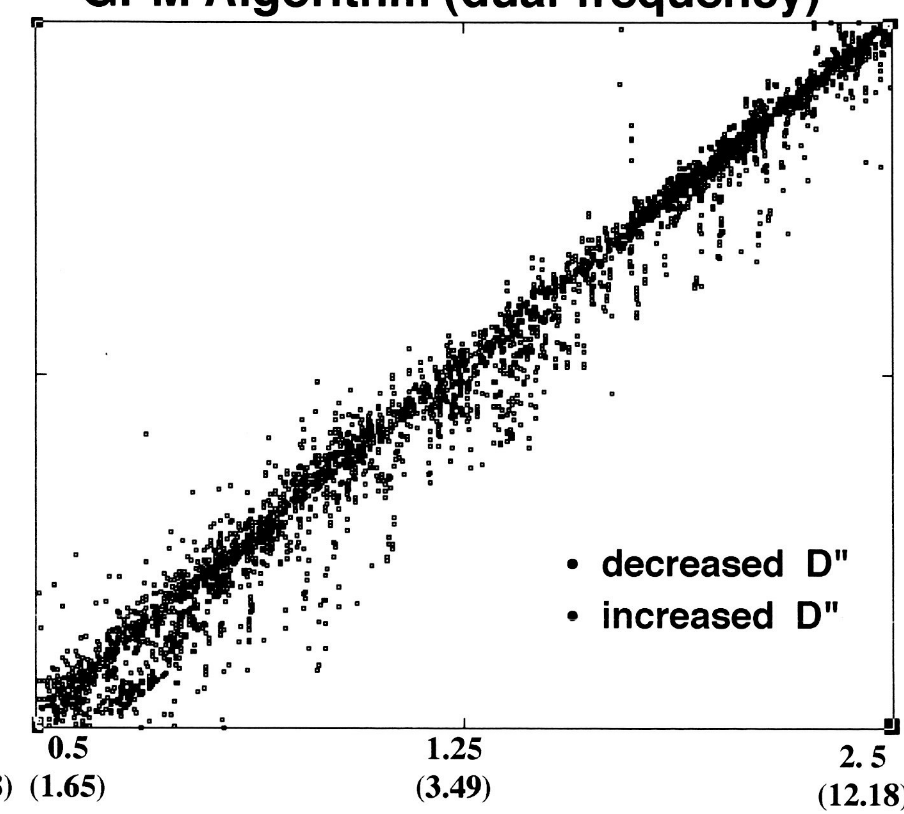
TRMM & GPM Retrieved Rainrates Presuming Interannual Perturbation in Rain Microphysics Associated with Shift of ENSO from Negative to Positive Phase

[formulated by decrease/increase in mean adj drop size]

TRMM Algorithm (single-frequency)



GPM Algorithm (dual-frequency)



average D" for black year is 0.95; average D" for red year is 1.2

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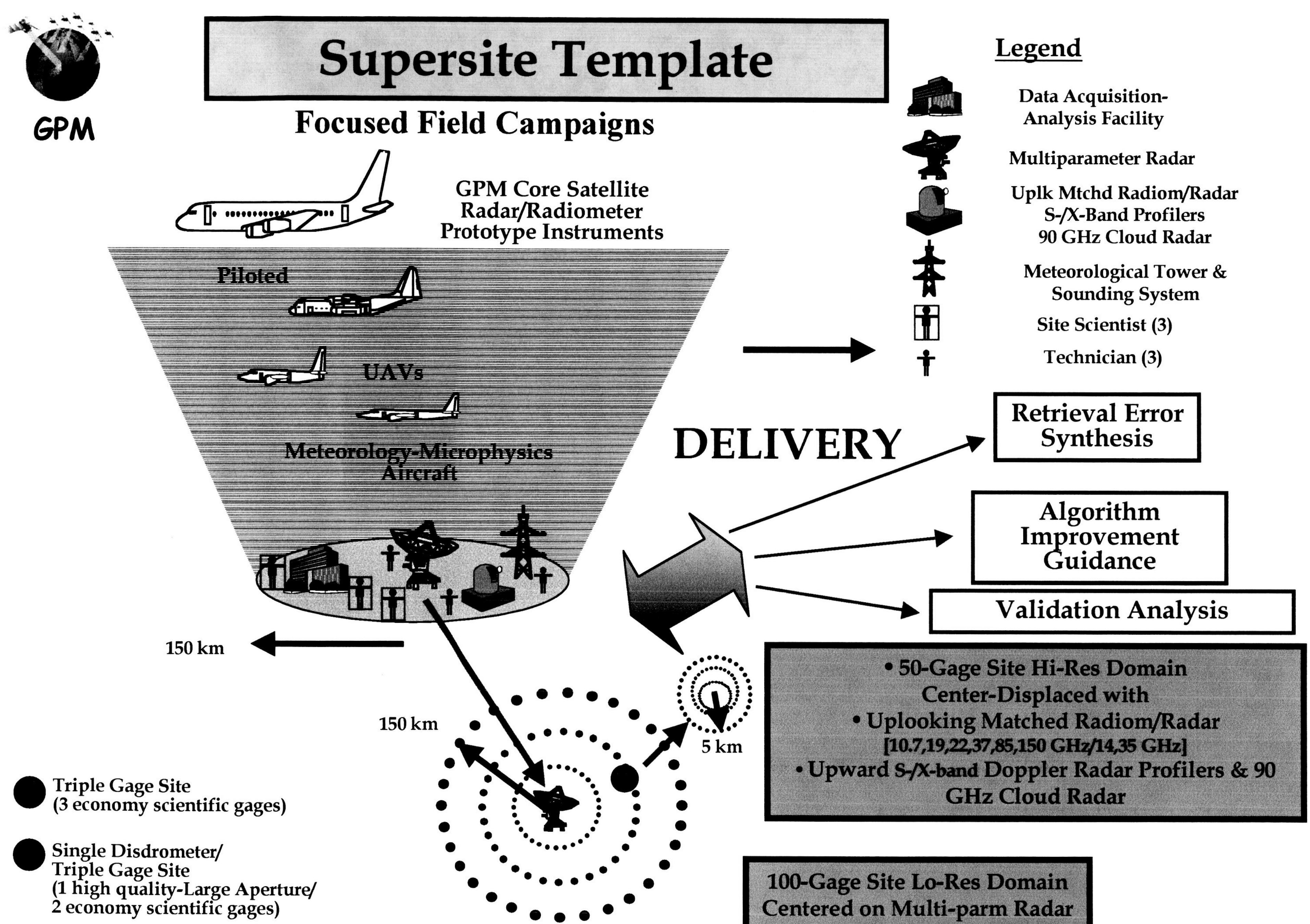
IV
Weather Prediction, Data Assimilation & GPM Validation Program

Supersite Template

Focused Field Campaigns



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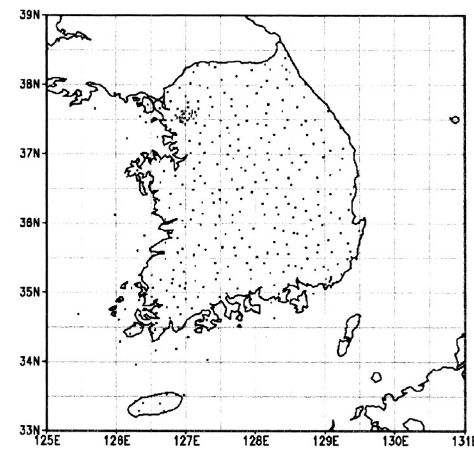
Error Characterization (Precision)

$$J(x) = (x^b - x)^T F^{-1} (x^b - x) + (y^o - H(x))^T (O + P)^{-1} (y^o - H(x))$$

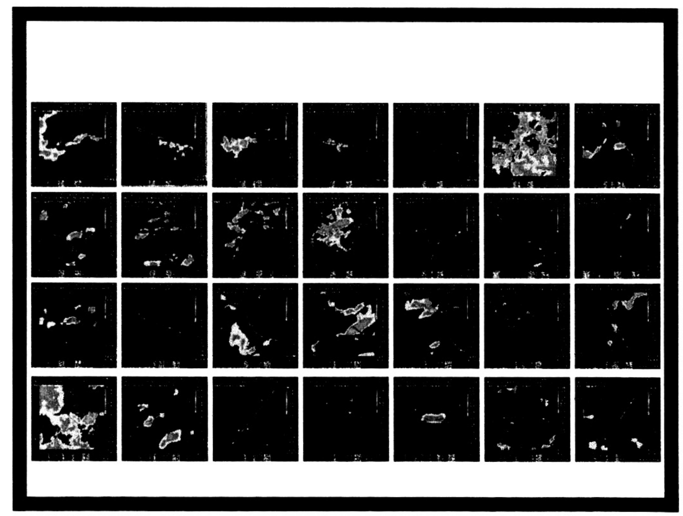
***F, O, & P* are error covariance matrices associated with forecast model, observations, & forward model (precip parameterization), where y^o, *H*, & *x* are observation, forward model, & control variable.**

One Minute Raingage Network over Korea



Space-Time Observational Error Covariance (*O*)

[redacted]

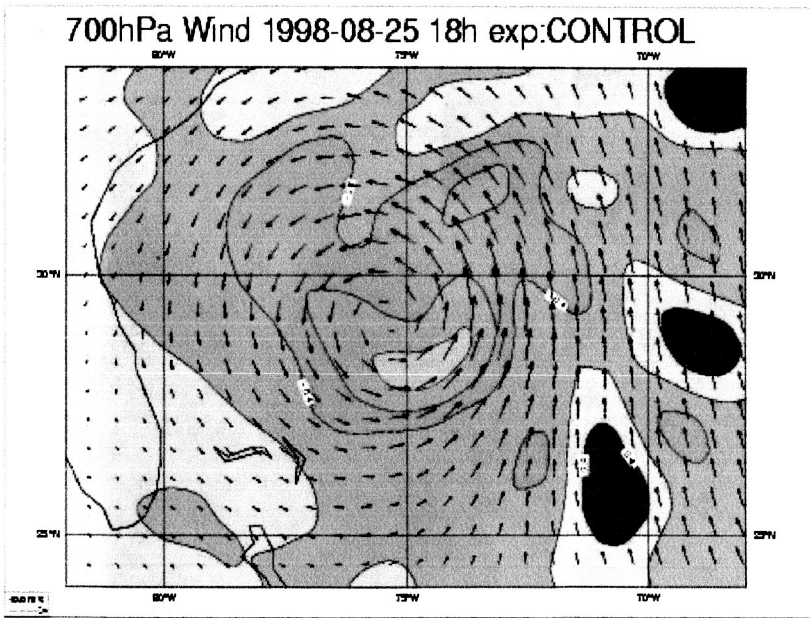


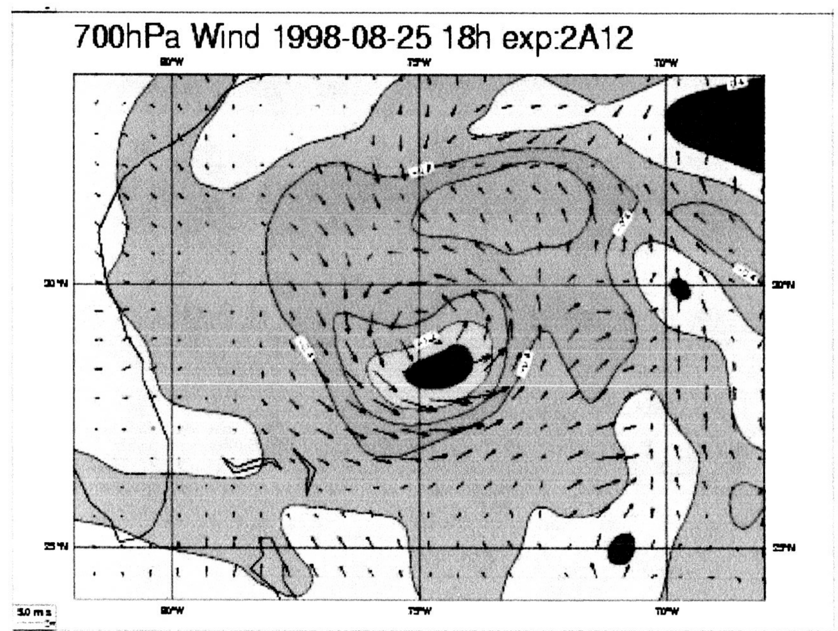
Space-Time Autocorrelation Structure Given By

- **volume scanning ground radars**
  (dual-polarization enables DPR calibration cross-checks)
- **research-quality, uniformly distributed, dense, & hi-frequency sampled raingage networks**

Impact of TMI Rain Assimilation on Tropical Cyclone Dynamics

Horizontal & Vertical Winds in Tropical Cyclone Bonnie





ECMWF

J.-F. Mahfouf

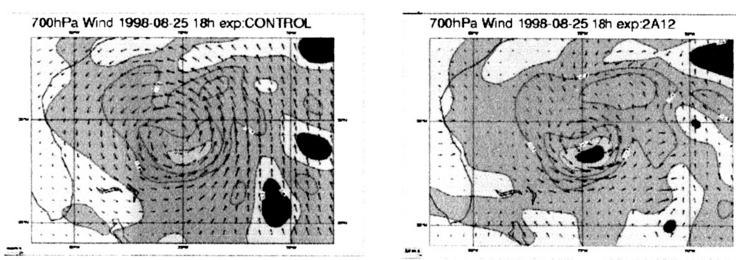
TRMM-SSM/I Data Assimilation

GPM

Hurricane Intensity (ECMWF) -- Mahfouf et al

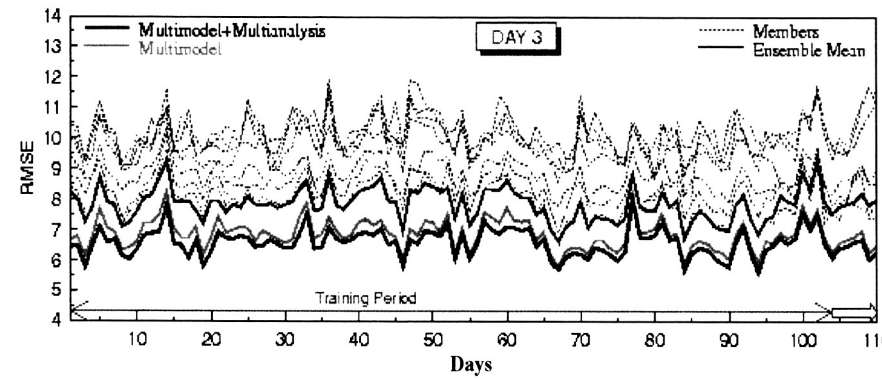
Impact of TMI Rain Assimilation on Tropical Cyclone Dynamics

Horizontal & Vertical Winds in Tropical Cyclone Bonnie



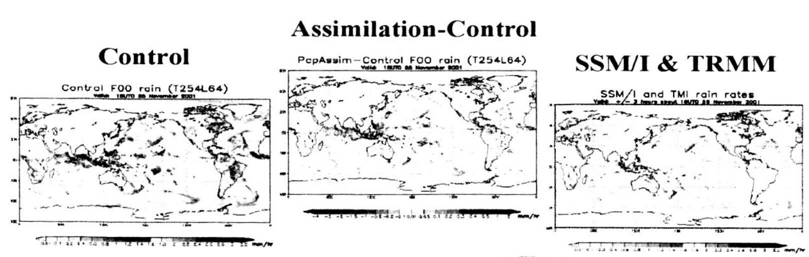
Hurricane Track (FSU) -- Krishnamurti et al

Superensemble: RMS Error of Global Precipitation (0 - 360E ; 90S - 90N)



Tropical Convection (NOAA/NCEP) -- Kuligowski et al

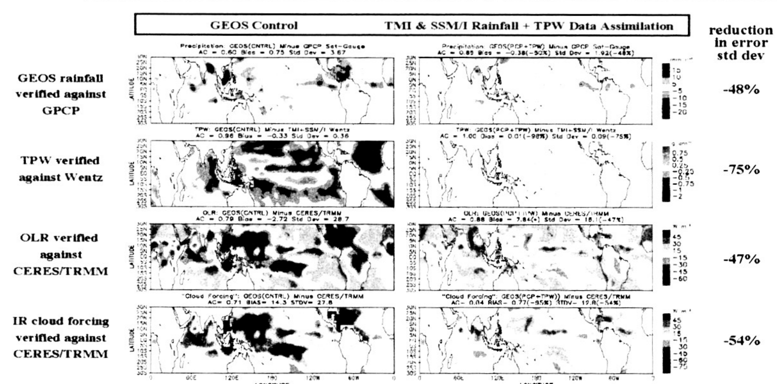
SSM/I & TRMM Data Assimilation Reduces Overprediction of Tropical Convection in NOAA GDAS Simulations



Courtesy of Bob Kuligowski, NOAA

Climate Re-analysis (NASA/DAO) -- Hou et al

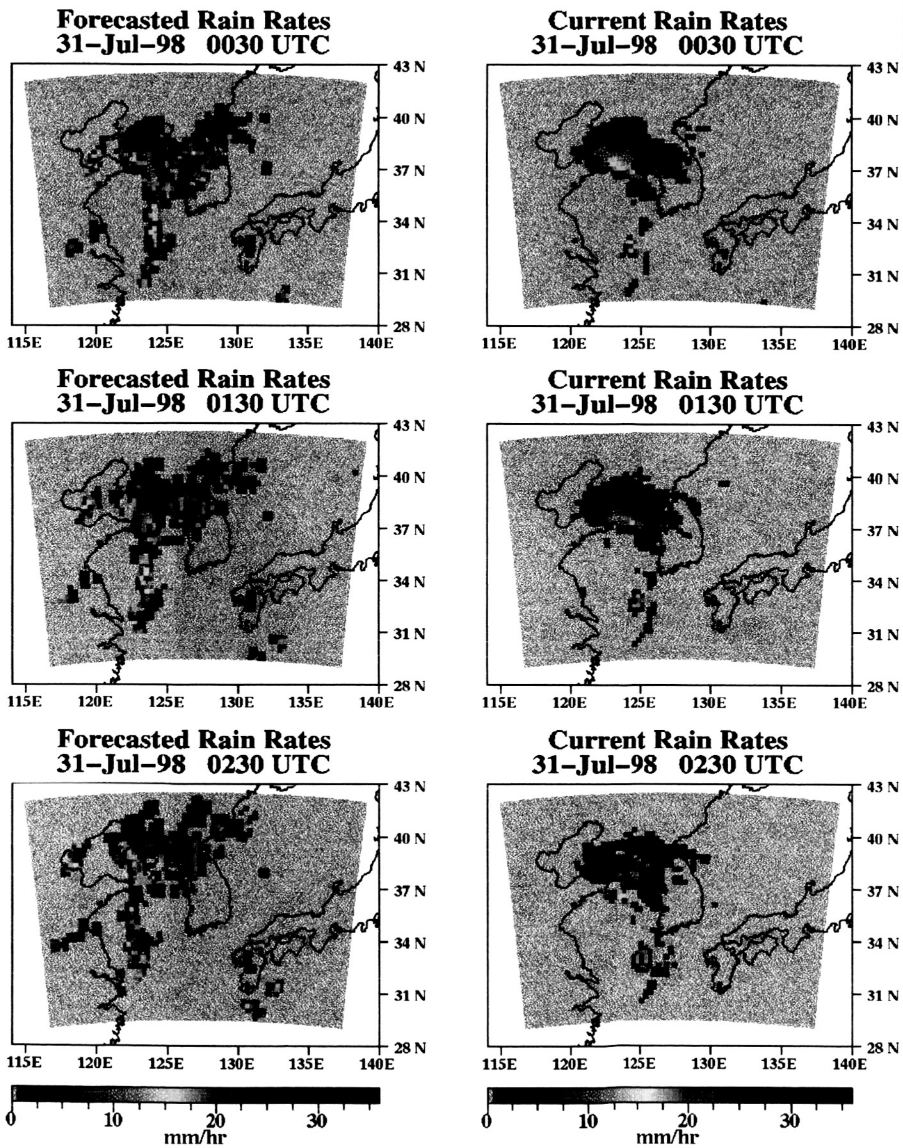
TRMM & SSM/I Rainfall + TPW Data Assimilation Improves Hydrological Parameters, Clouds, & TOA Radiation in GEOS Analysis



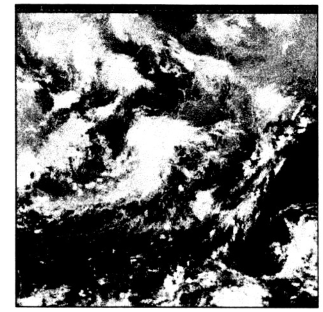
GSFC-DAO

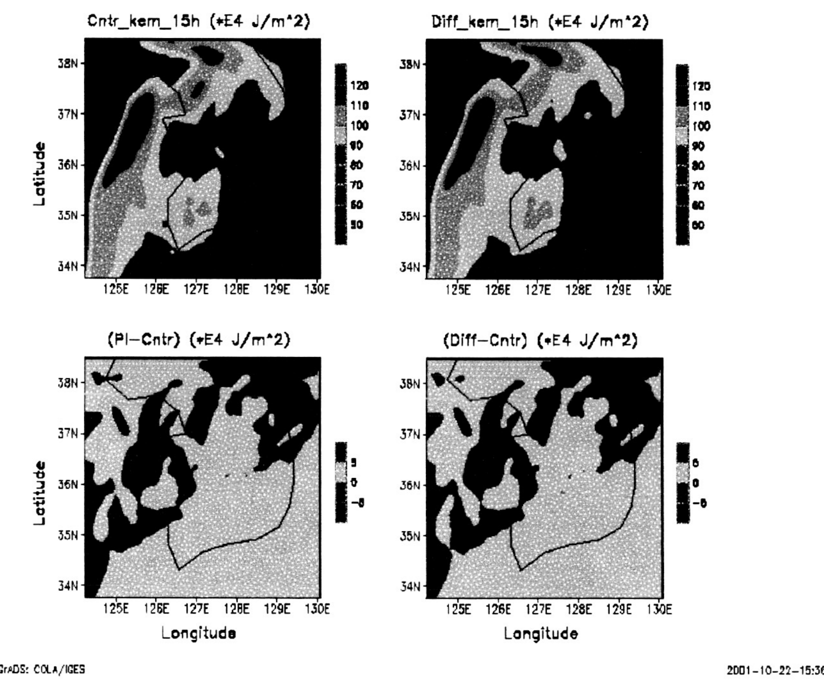
QPF Data Assimilation Experiments Over Korea

GPM



Using 3-hr rainfall predictions (nowcasts) from GMS to gain 3 hours of data initialization time in forecasts





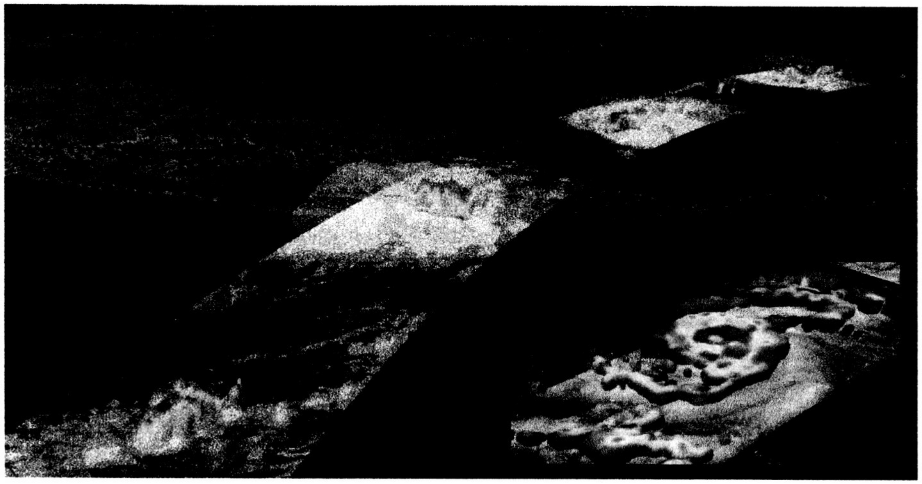
Ou, M., and E.A. Smith, 2003

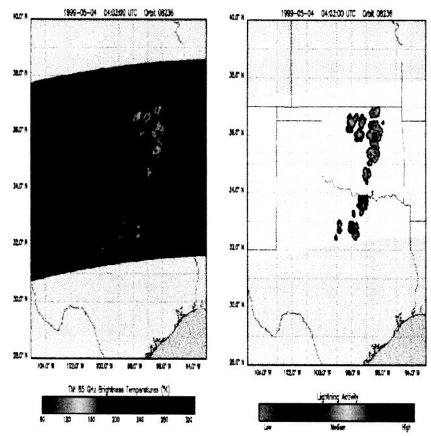
GPM

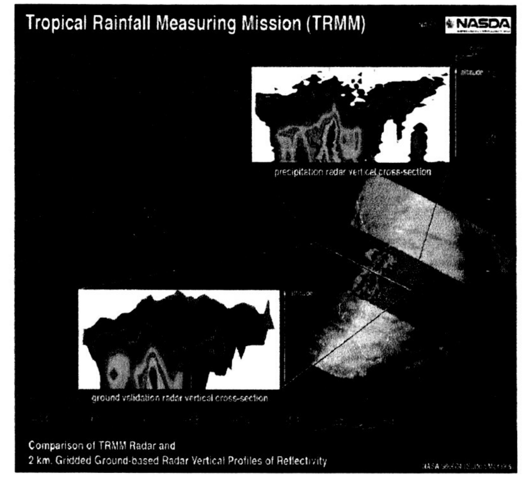
V
Hydrometeorlogical Prediction

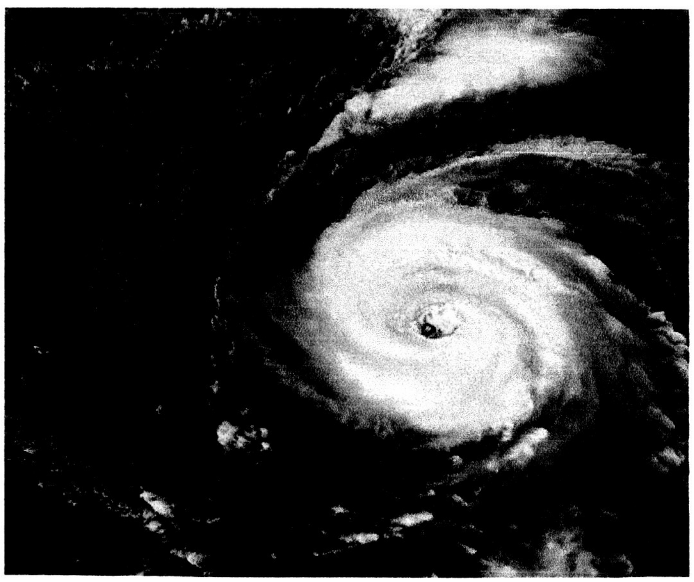
GPM

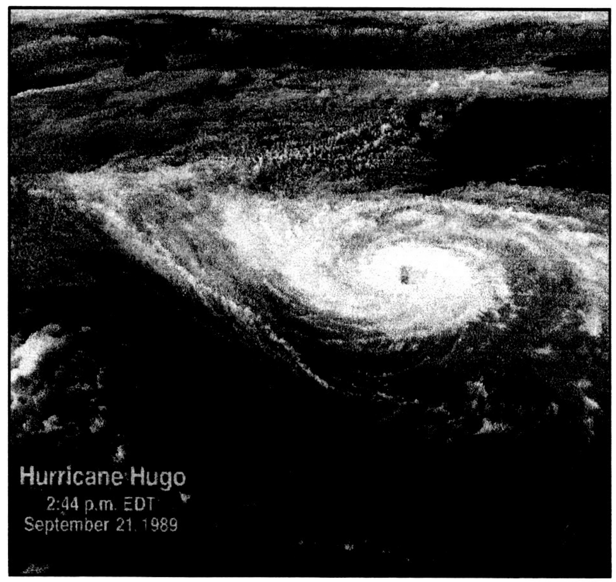
Prediction of Precipitation from Tropical or Tornadic Storms & Consequent Flooding is Foremost Concern of Many Nations







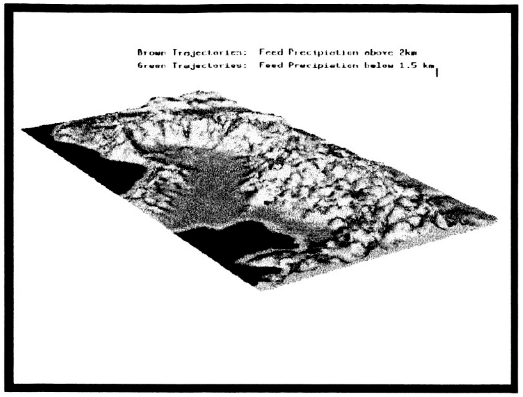




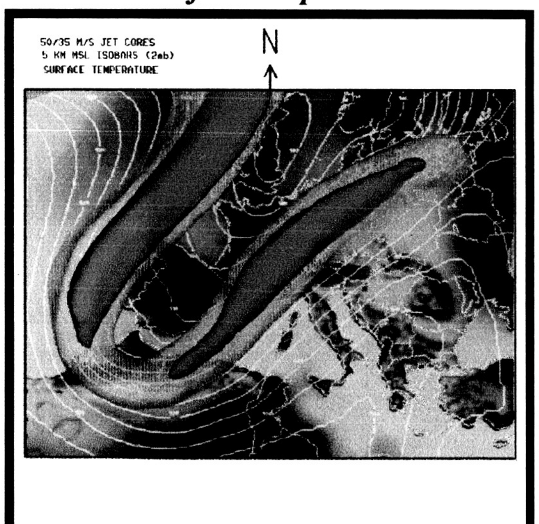
GPM

Better Flood Predictions:
CRM Simulation & Microphysical Analysis of Three (3) Late Season Mediterranean Floods

brown trajectories: > 2.0 km precipitation feed
green trajectories: < 1.5 km precipitation feed

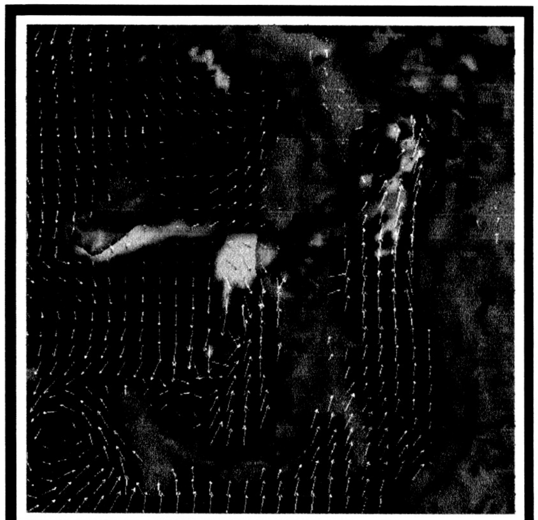


Amplifying Mesoscale Storms Arising within Mobile Westerly Disturbances under Control of Fixed Geography & Orography
35/50 m s^{-1} jet cores; 5 km MSL isobars (2 mb); surface temperature



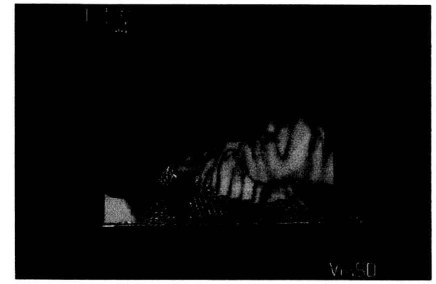
Piemonte - 2000

Simulation of Low-Level Flows within Tyrrhenian, Ligurian, Ionian, & Adriatic Seas
white (surface) -- orange (1.5 km)

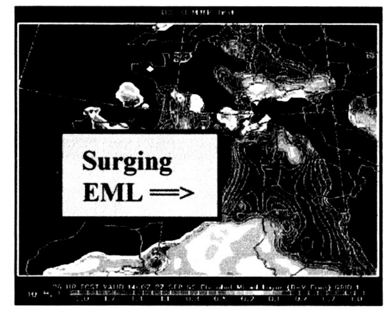


Friuli - 1998

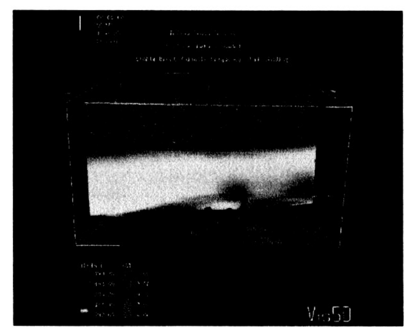
Barrier Convergence Zone
- *surface flow convergence set up off-shore*
- *due to flow normal to high alps terrain*
- *flow surge lifted over convergence zone off-shore (335 θ_e surface)*

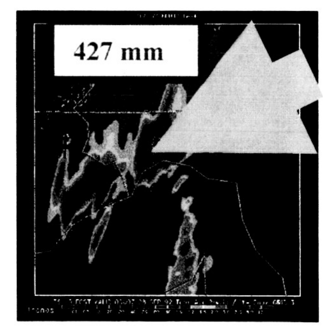


Elevated Mixed Layer
3 km MSL Brunt Vaisala Frequency



Inflow Cross-Section Surface θ_e (shaded)
Stable Brünt-Vaisala Frequency (dark shading)

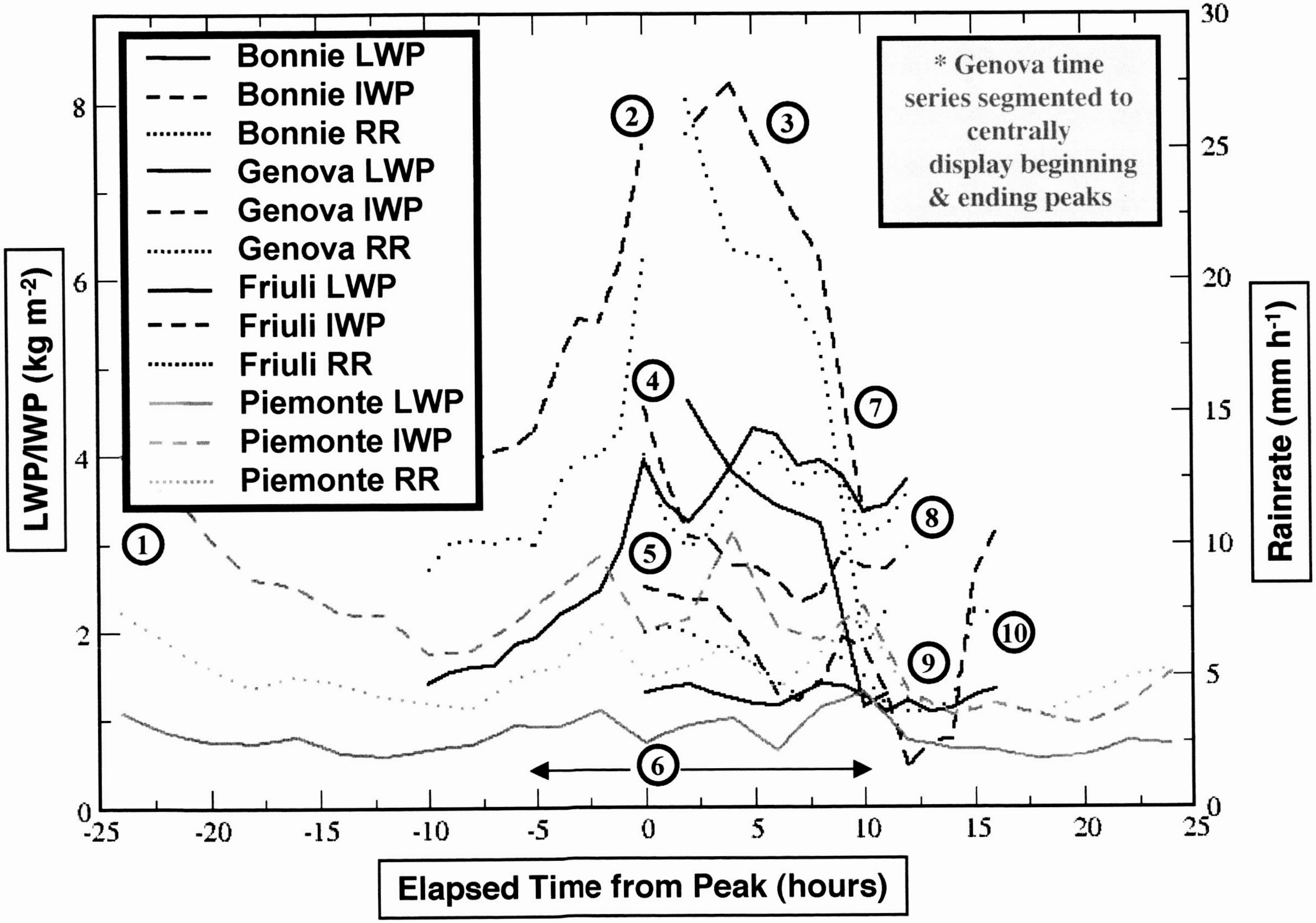




Genova - 1992

Average Liquid Water Path, Ice Water Path, & Rainrate

Hurricane Bonnie ('98), Genova MCS ('92), Friuli MCS ('98), & Piemonte ETS ('00)



1. Early Piemonte Convection (10-14-00/00 UTC)
2. Genova 2nd Peak @ Genova * (9-28-92/00 UTC)
3. Genova 1st Peak in France * (9-27-92/04 UTC)
4. Bonnie Peak (8-26-98/12 UTC)
5. Friuli Peak (10-6-98/20 UTC)
6. Piemonte Broad Stratiform Peak (10-14-00/19 to 10-15-00/10 UTC)
7. Genova Weakening Prior to 2nd Peak (9-27-92/13 UTC)
8. Bonnie @ Landfall (8-27-98/00 UTC)
9. Friuli Weakening @ Peak Elevation (10-7-98/08 UTC)
10. Friuli Break-up with Isolated Convection (10-7-98/12 UTC)

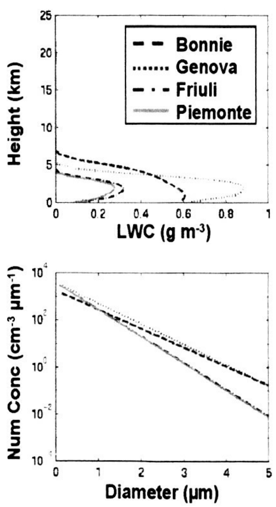
GPM

Between-Storm & Storm-Specific-Time Differences in Vertically-Distributed Microphysical & Vert-Velocity Properties [Rain Drops & Graupel Particles]

WATER CONTENT & SIZE DISTRIBUTION TOTAL STORM AREA (RR ≥ 1 mm h^{-1})

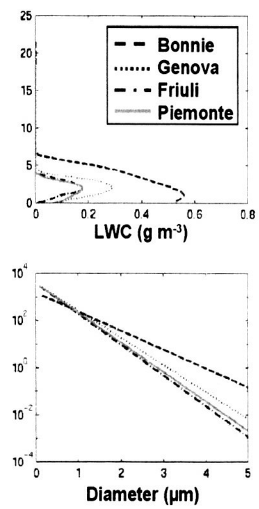
Rain Drops

INTENSE



DSD PROPERTIES (mm -- variable slope MP)		D_{mode}	D_{mean}	D_{eff}	ν
Bonnie	-	0.54	1.62	1	
Genova	-	0.50	1.49	1	
Friuli	-	0.38	1.15	1	
Piemonte	-	0.38	1.14	1	

WEAKENING

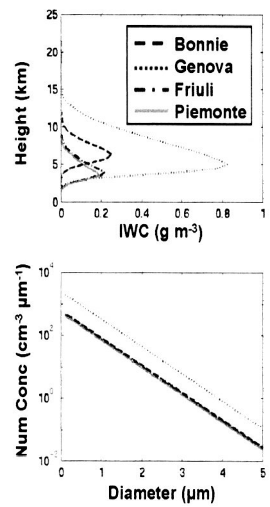


DSD PROPERTIES (mm -- variable slope MP)		D_{mode}	D_{mean}	D_{eff}	ν
Bonnie	-	0.54	1.62	1	
Genova	-	0.38	1.13	1	
Friuli	-	0.33	1.00	1	
Piemonte	-	0.35	1.04	1	

ICE CONTENT & SIZE DISTRIBUTION TOTAL STORM AREA (RR ≥ 1 mm h^{-1})

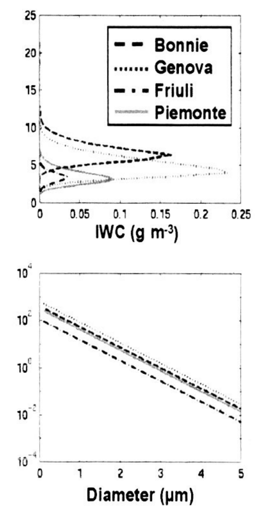
Graupel Particles

INTENSE



DSD PROPERTIES (mm -- constant slope MP)		D_{mode}	D_{mean}	D_{eff}	ν
Bonnie	-	0.50	1.50	1	
Genova	-	0.50	1.50	1	
Friuli	-	0.50	1.50	1	
Piemonte	-	0.50	1.50	1	

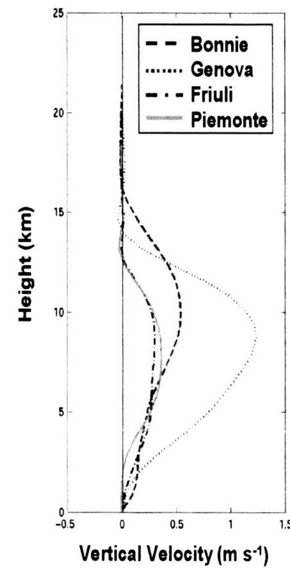
WEAKENING



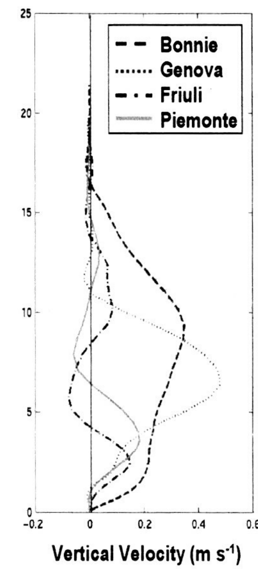
DSD PROPERTIES (mm -- constant slope MP)		D_{mode}	D_{mean}	D_{eff}	ν
Bonnie	-	0.50	1.50	1	
Genova	-	0.50	1.50	1	
Friuli	-	0.50	1.50	1	
Piemonte	-	0.50	1.50	1	

VERTICAL VELOCITY TOTAL STORM AREA (RR ≥ 1 mm h^{-1})

INTENSE



WEAKENING

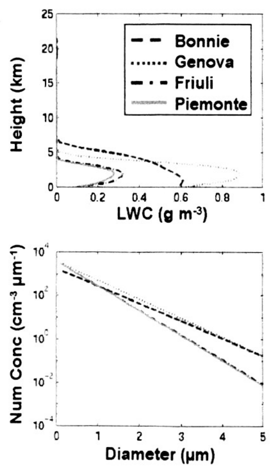


positive values indicate upward motion

Storm-Specific/Inter-Storm Differences in Vertically-Distributed Microphysical Properties
[Rain Drops]

WATER CONTENT & SIZE DISTRIBUTION TOTAL STORM AREA (RR ≥ 1 mm h^{-1})
Rain Drops

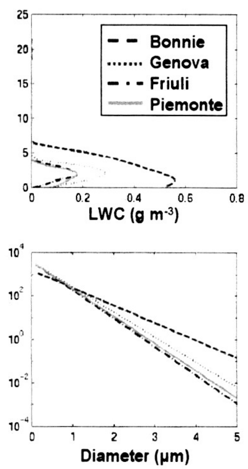
INTENSE



DSD PROPERTIES
(mm -- variable slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	0.54	1.62	1
Genova	-	0.50	1.49	1
Friuli	-	0.38	1.15	1
Piemonte	-	0.38	1.14	1

WEAKENING

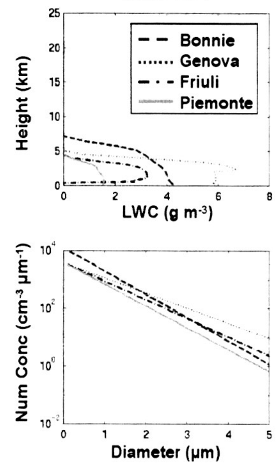


DSD PROPERTIES
(mm -- variable slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	0.54	1.62	1
Genova	-	0.38	1.13	1
Friuli	-	0.33	1.00	1
Piemonte	-	0.35	1.04	1

WATER CONTENT & SIZE DISTRIBUTION CENTRAL CONVECTION & EYEWALL
Rain Drops

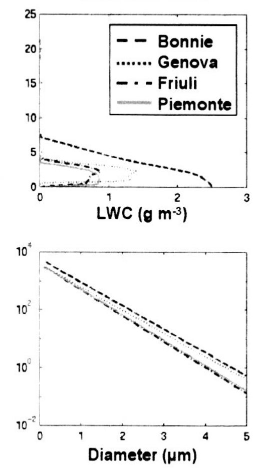
INTENSE



DSD PROPERTIES
(mm -- variable slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	0.54	1.62	1
Genova	-	0.83	2.49	1
Friuli	-	0.68	2.03	1
Piemonte	-	0.58	1.73	1

WEAKENING

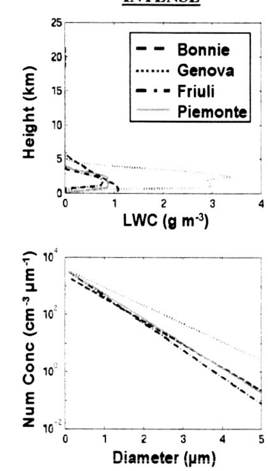


DSD PROPERTIES
(mm -- variable slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	0.54	1.62	1
Genova	-	0.55	1.64	1
Friuli	-	0.49	1.46	1
Piemonte	-	0.50	1.49	1

WATER CONTENT & SIZE DISTRIBUTION PERIPHERY & OUTER RAINBAND
Rain Drops

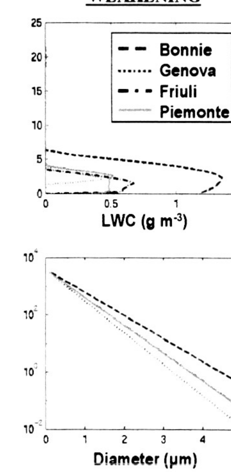
INTENSE



DSD PROPERTIES
(mm -- variable slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	0.54	1.62	1
Genova	-	0.68	2.06	1
Friuli	-	0.46	1.38	1
Piemonte	-	0.50	1.51	1

WEAKENING



DSD PROPERTIES
(mm -- variable slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	0.54	1.62	1
Genova	-	0.40	1.19	1
Friuli	-	0.45	1.35	1
Piemonte	-	0.45	1.34	1

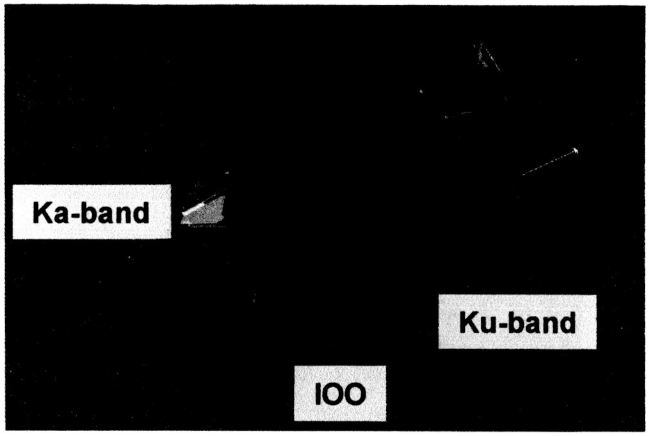
Conclusions

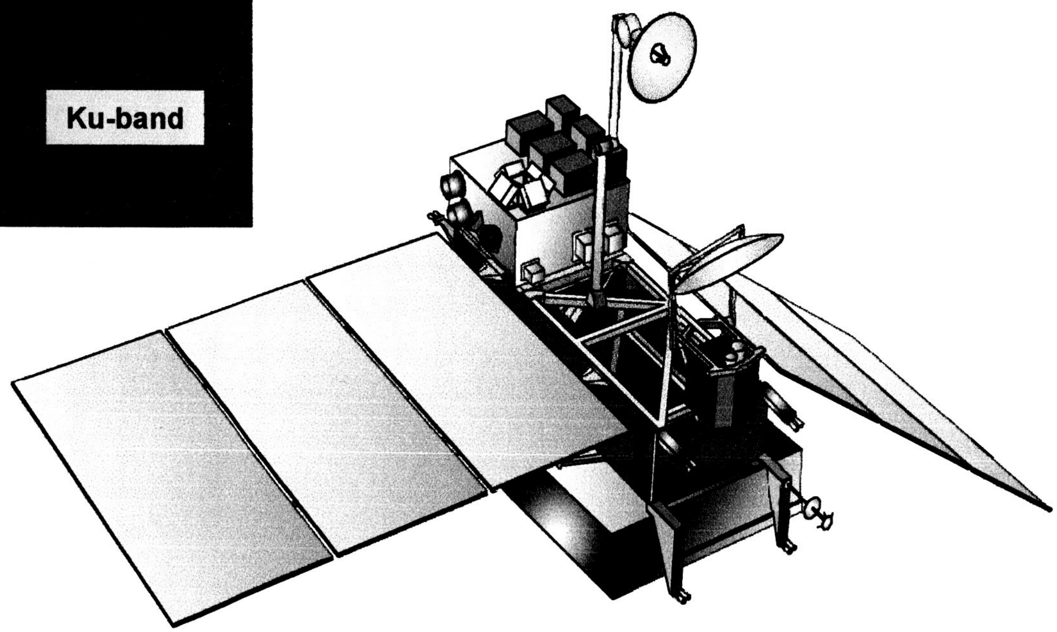
1. Global measurement coverage in conjunction with greater emphasis on spatial resolution & microphysical processes in retrieval will provide framework for implementing GPM research program focused on relationship between global water cycle & global climate variability.
2. Aggressive error reduction - error characterization validation program will provide quantitative conditional bias uncertainty/space-time error covariance information needed for objective rainfall data assimilation used in short and medium range weather forecasting.
3. 3-hour sampling & research emphasis on achieving basin/global scale water budget closure will improve accuracy of hydrometeorological prediction models & their application to assessment of fresh water resources, prediction of seasonal flood-drought conditions, & hazardous flood forecasts.
4. Although challenging, GPM mission data should reveal accelerations in global & regional water cycles -- if data time series are extended to decadal time scale, measurements become microphysics-centric, & research emphasis is given to closure of time derivative form of water budget.

GPM

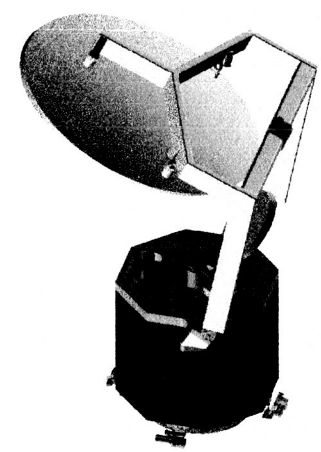
Backup Slides

GPM Core Satellite with GPM Microwave Imager (GMI) & Dual-Frequency Precipitation Radar (DPR)



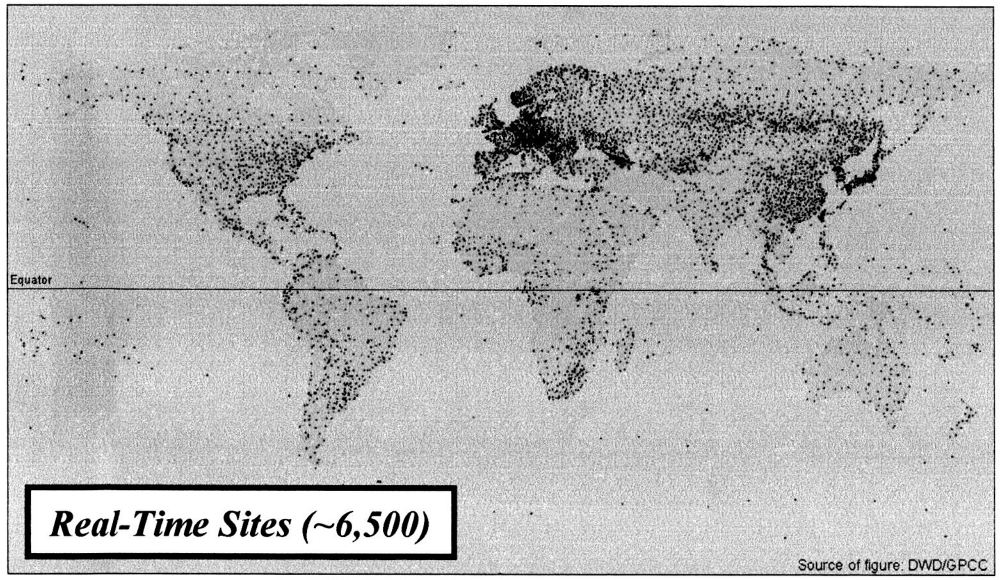


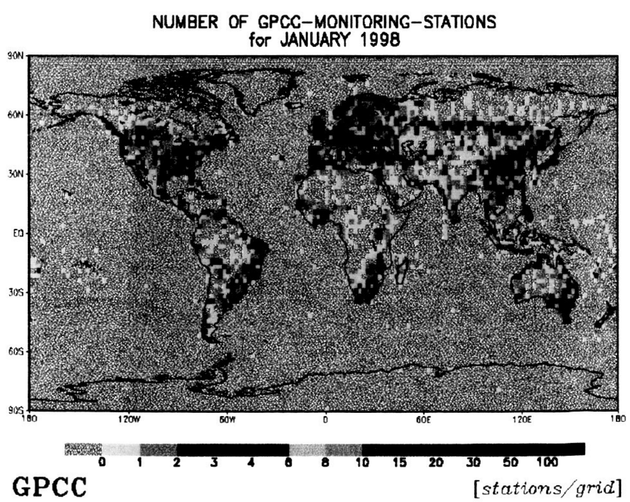
GMI Radiometer



Why GPM?

Global Precipitation Climatology Center (GPCC) Global Rain Gauge Distribution
[~6, 500 Real-Time Sites; ~38,000 Full-Network Sites]





Single Gauge Catchment Area

Ave Rain Gauge Radius (R) $\approx$ 10 cm
Mean Gauge Catchment Area $\approx 0.031415\ m^2$

Cumulative Gauge Catchment Area

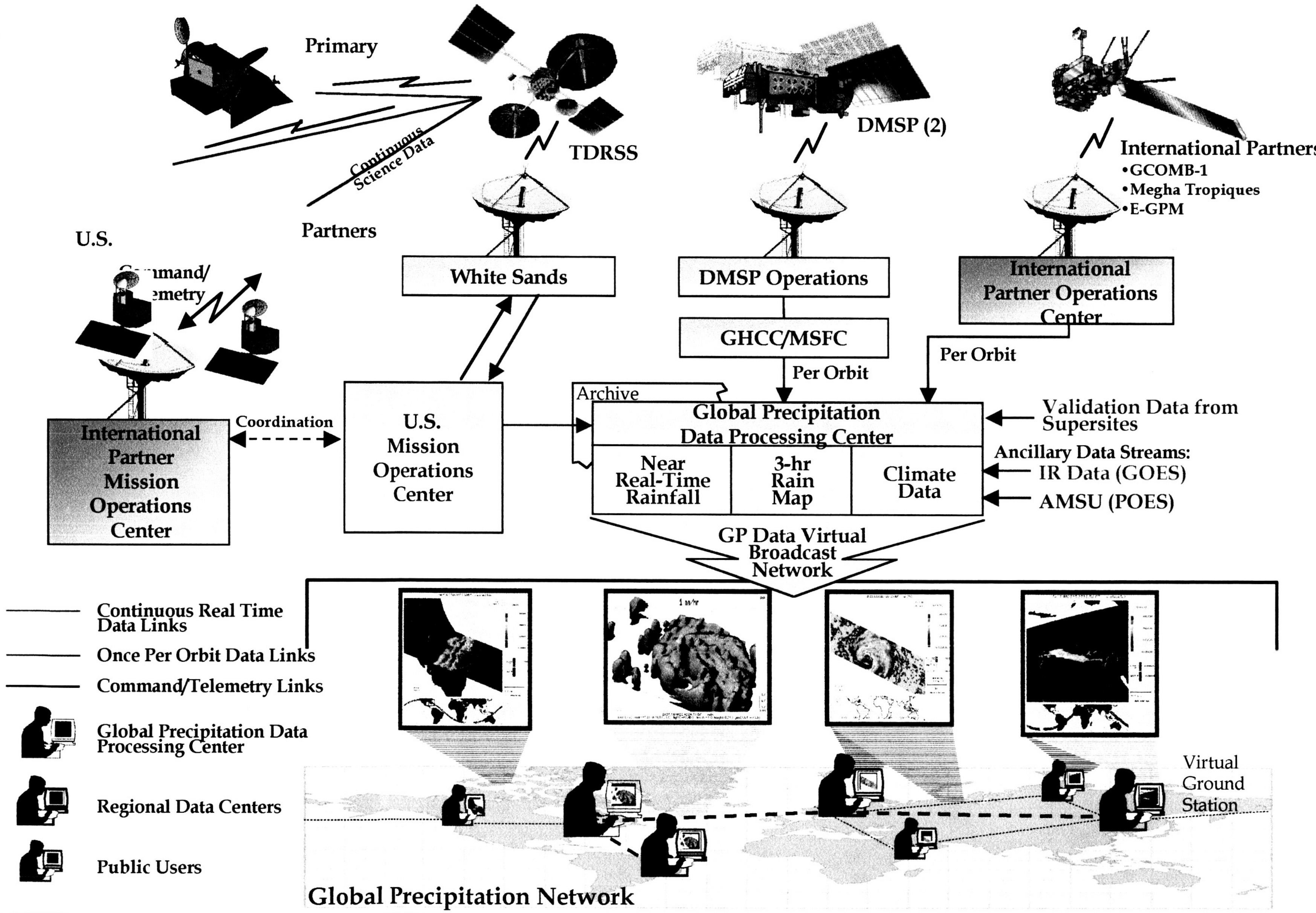
total catchment area of 13,000 U.S. gauges $\approx 400\ m^2$ (~20 m x 20 m)
total catchment area of 39,000 global gauges $\approx 1{,}200\ m^2$ (~35 m x 35 m)

Familiar Areal References

standard tennis court dimensions $\equiv$ 10.97 m x 23.77 m

standard basketball court dimensions $\equiv$ 28 m x 15 m

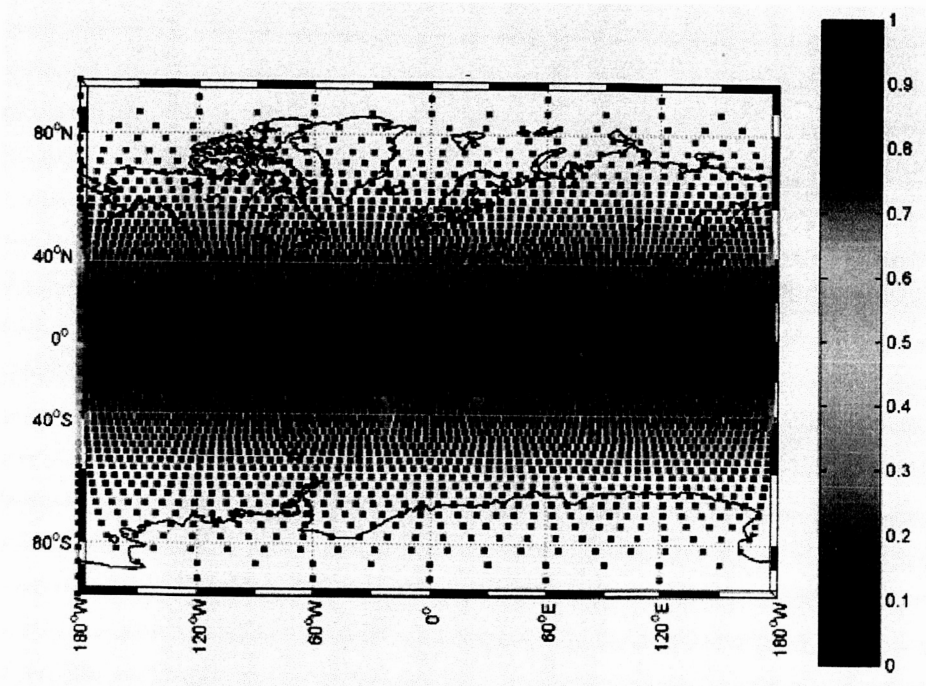
Mission Overview



Percentage of 3-Hour Intervals Sampled in 7-Day Period

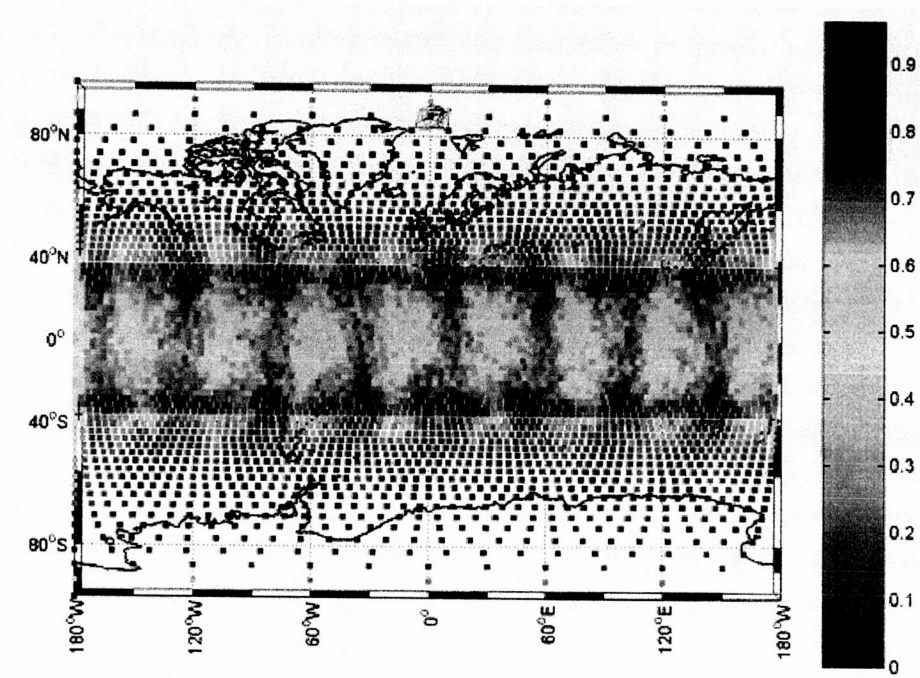
Precipitation Sampling Worldwide: Constant Area Pixels

GPM Era



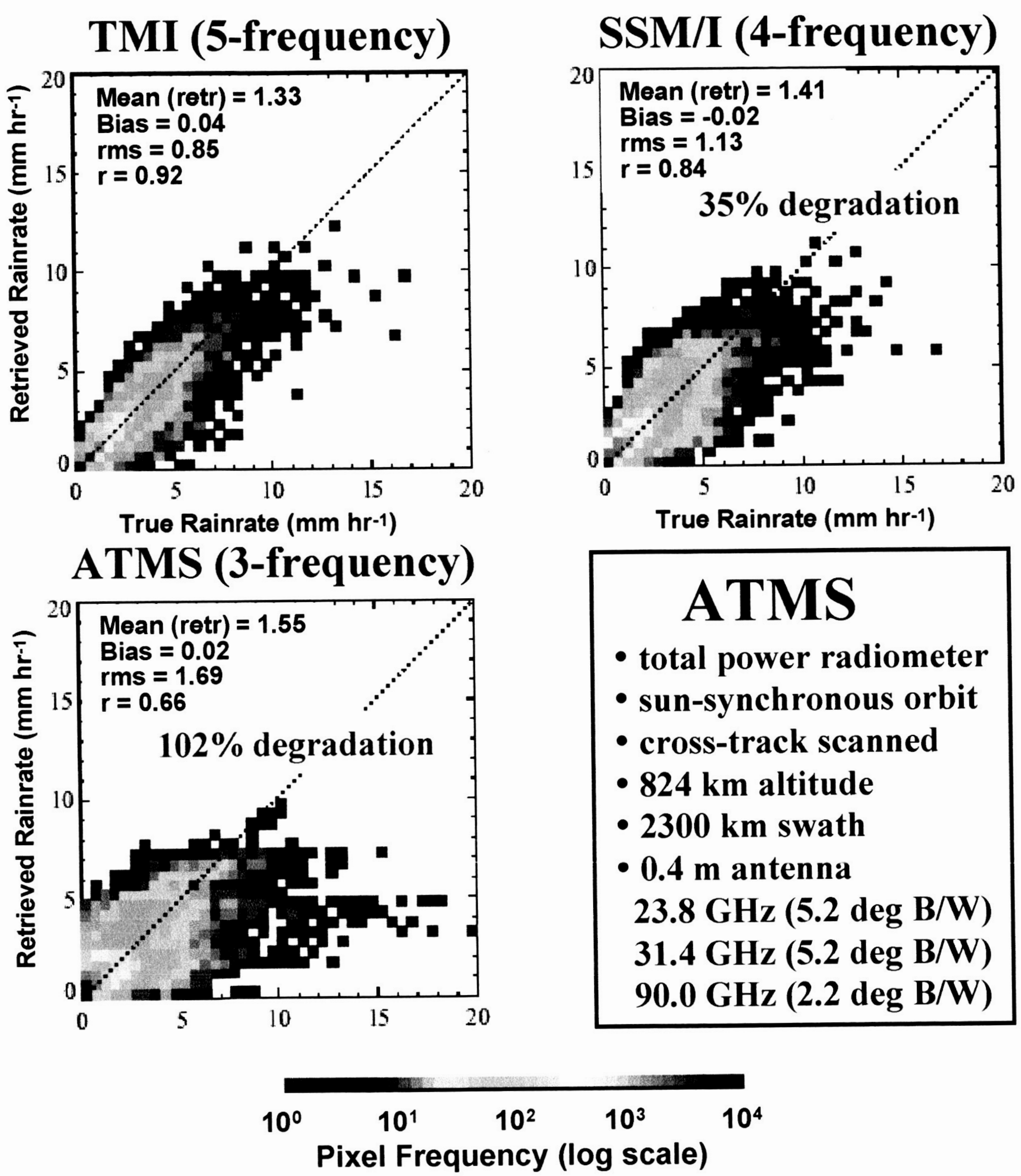
GPM Core, DMSP-F18 & -F19, GCOM-B1, Megha-Tropiques, & 3 600-km Drones

EOS Era



TRMM, DMSP-F13, -F14, & -F15, Aqua, & ADEOS-II

Assessment of ATMS as Rain Instrument



ATMS

- total power radiometer
- sun-synchronous orbit
- cross-track scanned
- 824 km altitude
- 2300 km swath
- 0.4 m antenna

23.8 GHz (5.2 deg B/W)
31.4 GHz (5.2 deg B/W)
90.0 GHz (2.2 deg B/W)

GPM

Top Panel: TRMM Measurement of Hurricane Bonnie (8/22/98)

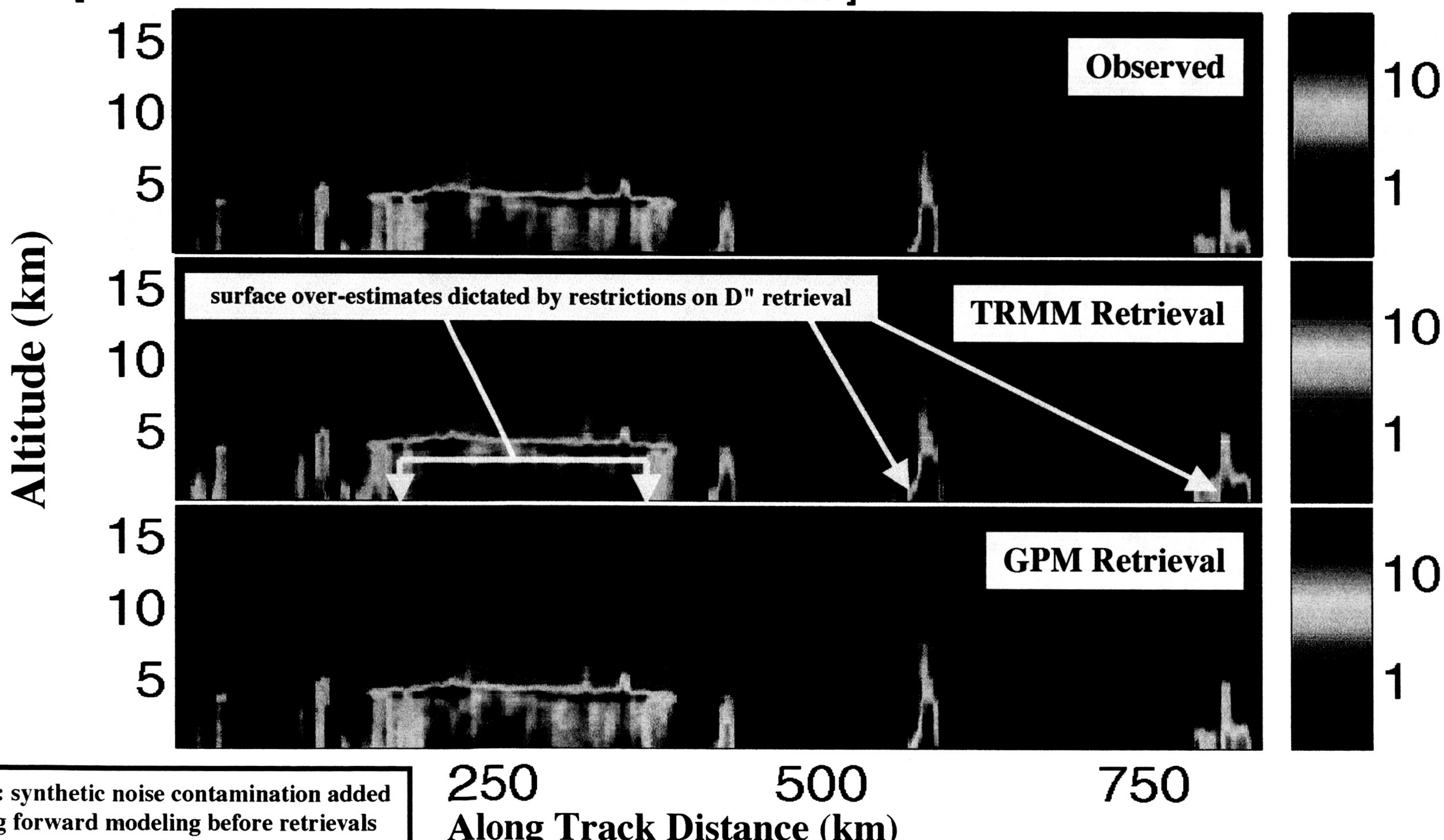
[based on TRMM Comb Alg 2B31 with resolution enhancement & mass-weighted mean adj drop diameter (D") assumed to decrease from surface to freezing level]

Middle Panel: Single-Frequency TRMM Combined Retrieval Algorithm

[restricted to retrieve invariant D" with altitude]

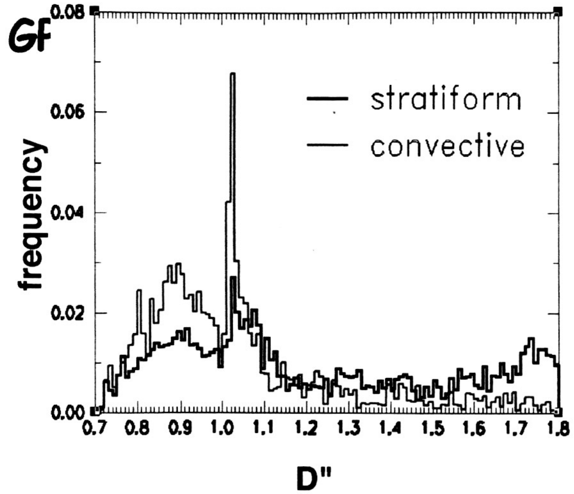
Bottom Panel: Dual-Frequency GPM Combined Retrieval Algorithm

[allowed to retrieve variation in D" with altitude]



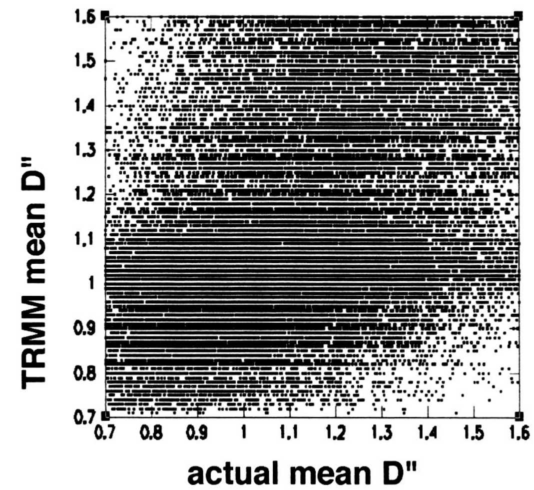
NOTE: synthetic noise contamination added during forward modeling before retrievals

TRMM vs GPM Estimates of DSD Variability

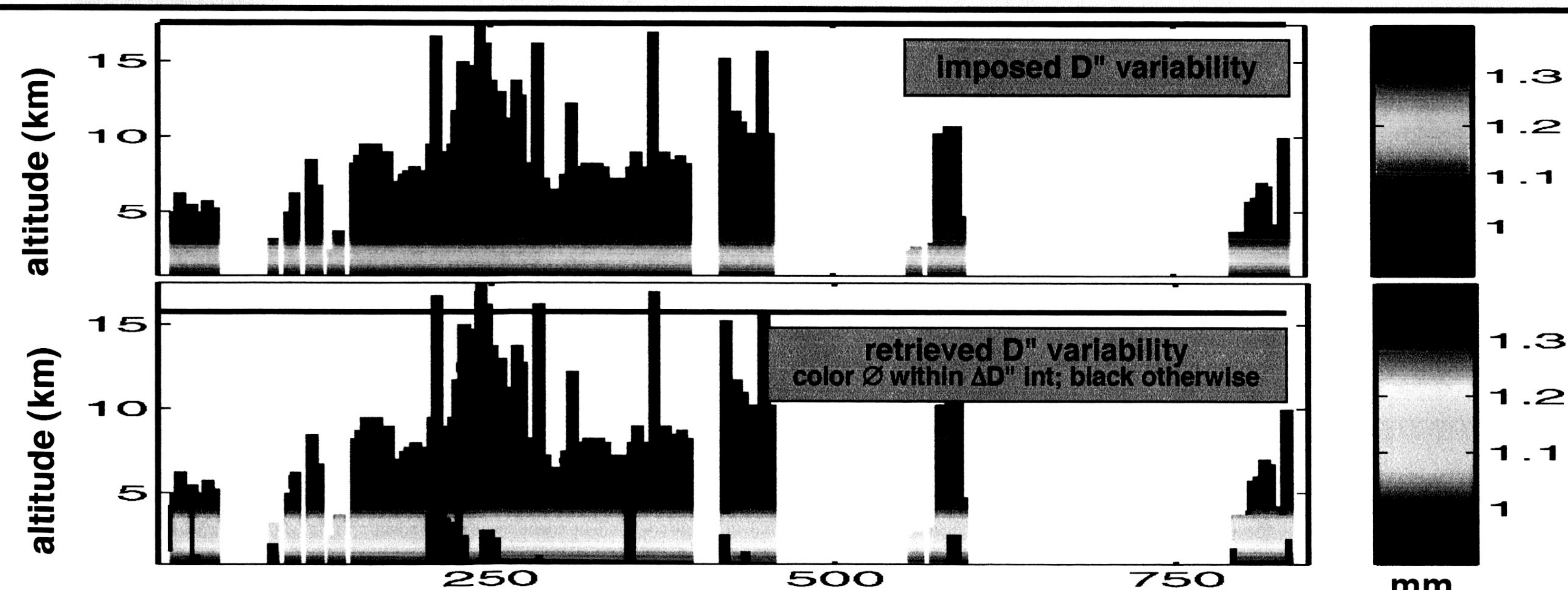


By combining PR-based (SRT) estimates with TMI-based estimates of total path attenuation (PIA), TRMM algorithm makes coarse estimates of mean adj drop diameter (D"). Results hint at possible systematic variability (left panel) -- but lack of differential reflectivity signal leads to two problems (right panel):

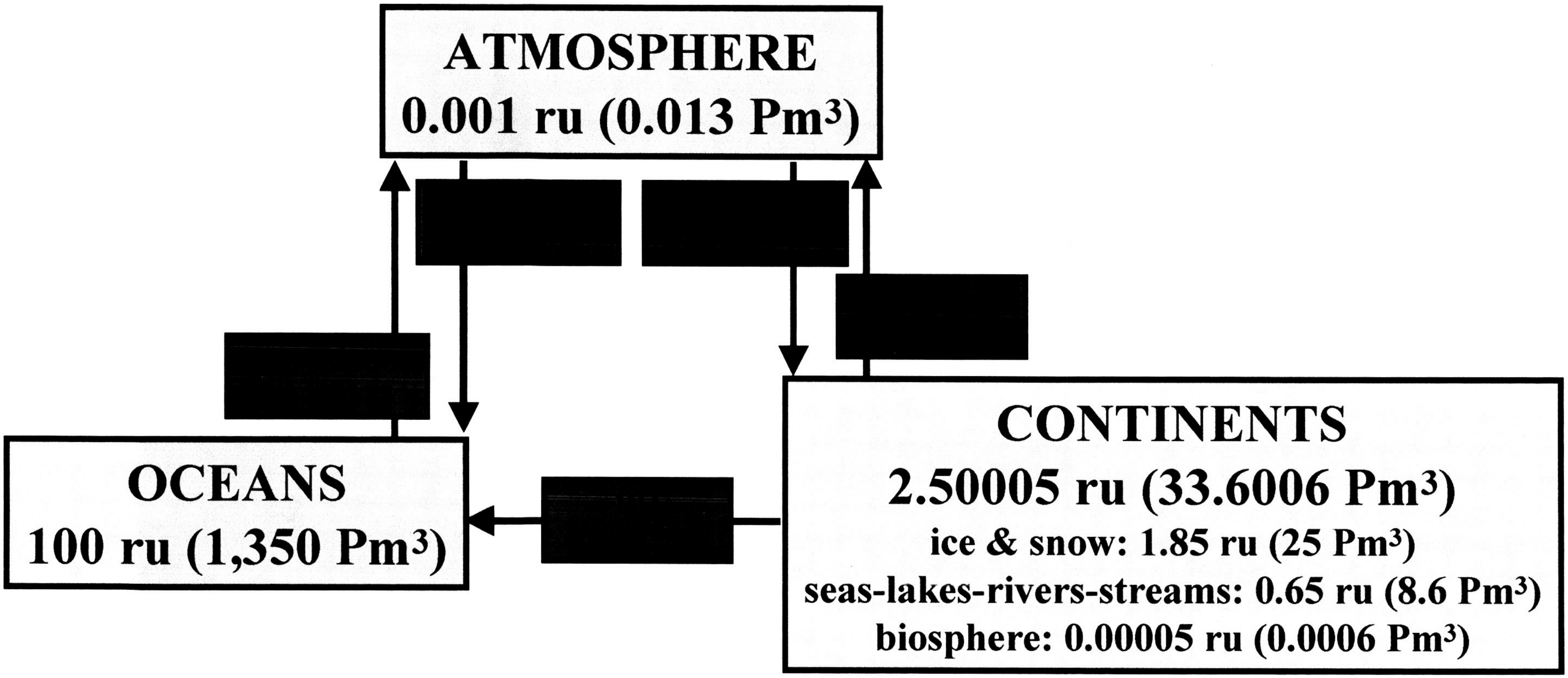
(a) significant uncertainties
(b) unresolved vertical variability



GPM algorithm mitigates both problems as shown in example from Bonnie simulation



Global Water Budget



Notes:
(a) global uncertainties order ±25%
(b) transfers some 0.025-0.0025% of ocean reservoir
(c) ru ≡ relative units

GPM

Verifying Accelerations in Water Cycle Will Require Convergence of Different Analysis Procedures

1. trend analysis of lengthy precipitation time series
2. balancing time-derivative forms of water balance eqns
3. detecting substantive changes in rain DSD properties

GPM

GPM Validation Strategy

I. Basic Rainfall Validation
- Raingauges/Radars

new/existing gauge networks
new/existing radar networks

Research Quality Data →

Confidence
sanity checks

II. GPM Supersites
- Basic Rainfall Validation

hi-lo res gauge/disdrometer networks
polarametric Radar system
- Accurate Physical Validation

scientists & technicians staff
data acquisition & computer facility
meteorological sensor system
upfacing multifreq radiometer system
D_0/DSD variability/vertical structure
convective/stratiform partitioning

GPM Satellite Data Streams

Continuous Synthesis
- error variances
- precip trends

Calibration

Supersite Products

Algorithm Improvements

III. GPM Field Campaigns
- GPM Supersites

cloud/ precip/radiation/dynamics processes
- GPM Alg Problem/Bias Regions

targeted to specific problems

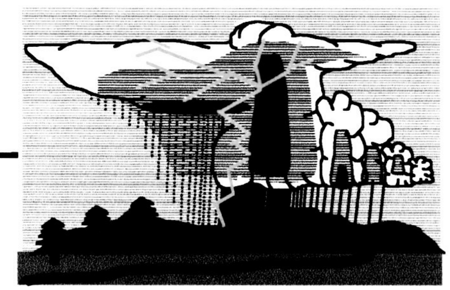
FC Data

Research
- cloud macrophysics
- cloud microphysics
- cloud-radiation modeling

Tropical Continental

Tropical Oceanic

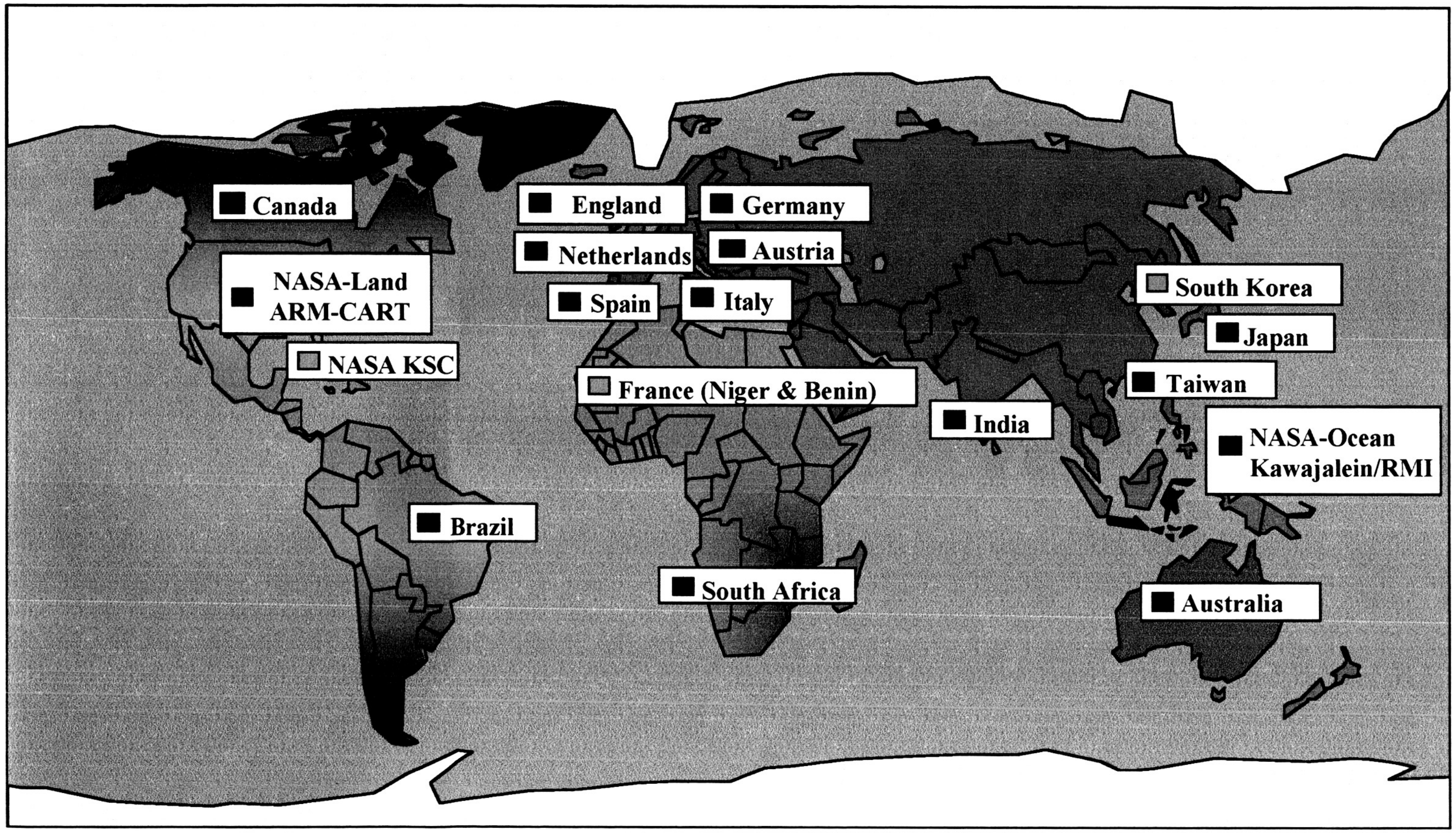
Mid-Lat Continental



Extratropical Baroclinic

High Latitude Snow

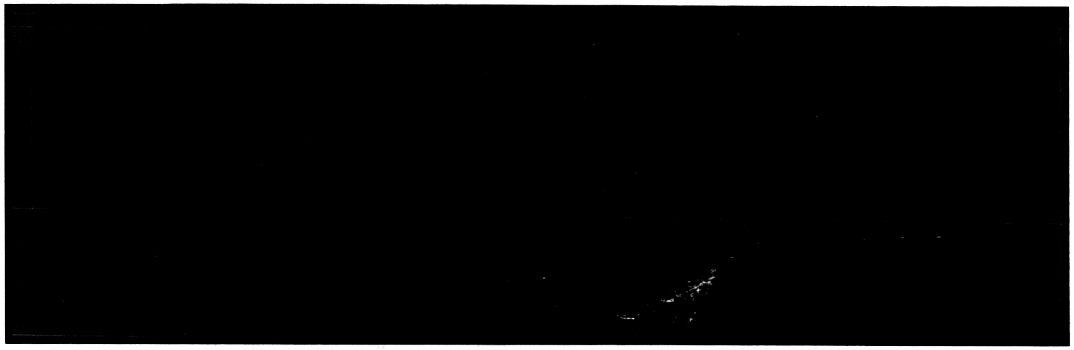
Potential GPM Validation Sites



■ Supersite ■ Regional Raingage Site ■ Supersite & Regional Raingage Site

Error Characterization (Accuracy)

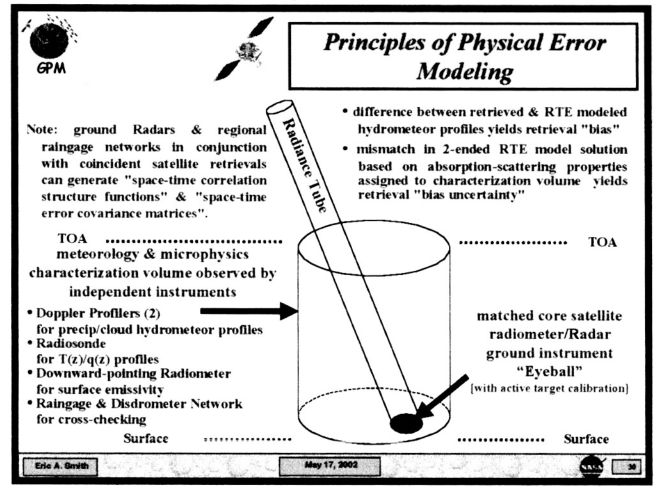
Bias (B) & Bias Uncertainty (ΔB)



based on:

- **physical error model (passive-active RTE model)**
- **matched satellite radiometer/radar instrument on ground with continuous calibration (eyeball)**
- **independent measurements of observational inputs needed for error model (DSD profile, T-q profile, surface)**

Based on Physical Error Model

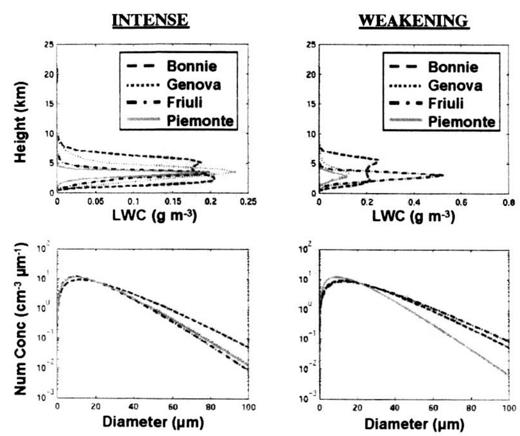


All retrievals from constellation radiometers & other satellite instruments are bias-adjusted according to bias estimate from reference algorithm for core satellite.

Hydrometeor-Specific Differences in Vertically-Distributed Microphysical Properties [Cloud Droplets, Aggregates, Pristine Crystals]

WATER CONTENT & SIZE DISTRIBUTION TOTAL STORM AREA (RR ≥ 1 mm h^{-1})

Cloud Droplets



INTENSE — DSD PROPERTIES (µm -- gamma)

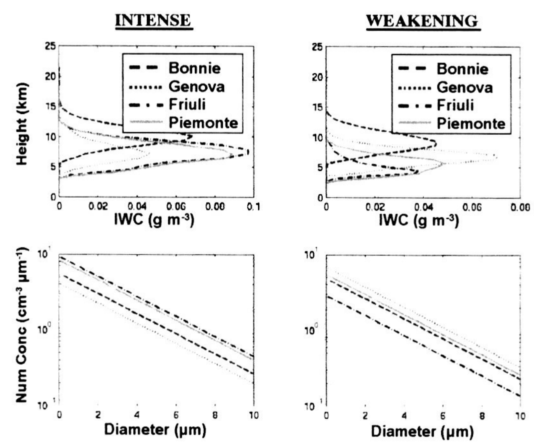
	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	12.0	24.0	48.0	2
Genova	10.0	20.0	40.0	2
Friuli	9.48	19.0	37.9	2
Piemonte	9.91	19.8	39.6	2

WEAKENING — DSD PROPERTIES (µm -- gamma)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	12.0	24.0	48.0	2
Genova	9.13	18.3	36.5	2
Friuli	13.0	26.0	52.0	2
Piemonte	9.18	18.4	36.7	2

ICE CONTENT & SIZE DISTRIBUTION TOTAL STORM AREA (RR ≥ 1 mm h^{-1})

Aggregates



INTENSE — DSD PROPERTIES (mm -- constamt slope MP)

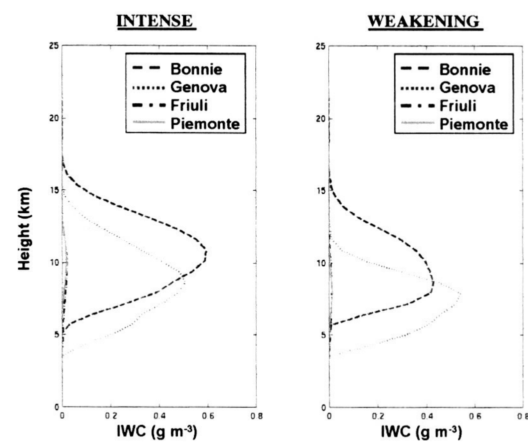
	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	3.30	9.90	1
Genova	-	3.30	9.90	1
Friuli	-	3.30	9.90	1
Piemonte	-	3.30	9.90	1

WEAKENING — DSD PROPERTIES (mm -- constamt slope MP)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	-	3.30	9.90	1
Genova	-	3.30	9.90	1
Friuli	-	3.30	9.90	1
Piemonte	-	3.30	9.90	1

ICE CONTENT & SIZE DISTRIBUTION TOTAL STORM AREA (RR ≥ 1 mm h^{-1})

Pristine Crystals



INTENSE — DSD PROPERTIES (mm -- monodisperse)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	0.24	0.24	0.24	0
Genova	0.24	0.24	0.24	0
Friuli	0.24	0.24	0.24	0
Piemonte	0.24	0.24	0.24	0

WEAKENING — DSD PROPERTIES (mm -- monodisperse)

	D_{mode}	D_{mean}	D_{eff}	v
Bonnie	0.24	0.24	0.24	0
Genova	0.24	0.24	0.24	0
Friuli	0.24	0.24	0.24	0
Piemonte	0.24	0.24	0.24	0